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A list of catalogues of meteorite collections.

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THE earliest systematic catalogue of meteorite collections is that of Otto Buchner[1] in 1863, in which he listed 264 meteorites preserved in 89 collections. Thirty years later E. A. Wülfing, after circularizing 350 mineralogical and other collections, gave preliminary results[2] for more than 500 meteorites with a total weight of 18,514 kilograms (18½ metric tons) preserved in 105 collections. This information was further elaborated in his valuable book[3] in 1897, in which is given the weight in grams of individual meteorites in each collection.

At that time Wülfing recognized 536 known meteorites. Now there are very many more—1347 according to the latest published list (C. F. Leonard, 1946, below) and 46 others have been noticed in 'Mineralogical Abstracts' since 1940. Wülfing's data, compiled for July 1893, is now, after more than half a century, much more out of date than he found Buchner's data after an interval of thirty years. To digest all the information now available would be an enormous task. All that I have

[1] C. L. O. Buchner, Die Meteoriten in Sammlungen, ihre Geschichte, mineralogische und chemische Beschaffenheit. Leipzig, 1863, xxvi+202 pp. Appendices 1–4 in Pogg. Ann., 1864–69, vols. 122, 124, 132, 136.

[2] E. A. Wülfing, Verbreitung und Wert der in Sammlungen aufbewahrten Meteoriten. Jahresh. Ver. Naturk. Württemberg, 1895, vol. 51, pp. 338–358 (preprint, 1894, pp. 1–21).

[3] E. A. Wülfing, Die Meteoriten in Sammlungen und ihre Literatur, nebst einem Versuch den Tauschwert der Meteoriten zu bestimmen. Tübingen, 1897, xlvi+461 pp. In addition to a general bibliography (pp. xxviii–xlvi) there are detailed bibliographies under each individual meteorite (pp. 1–405) and a list of the several collections (pp. 408–429).

attempted to do is to collect together the bibliographical references, leaving to some one else the task of working out all the details. I had some years ago compiled a skeleton list for my own use. Now that an International Commission on Meteorites has been set up by the International Geological Congress (eighteenth session in London, 1948) this list has been extended in the hope that it may be of general use for purposes of reference.

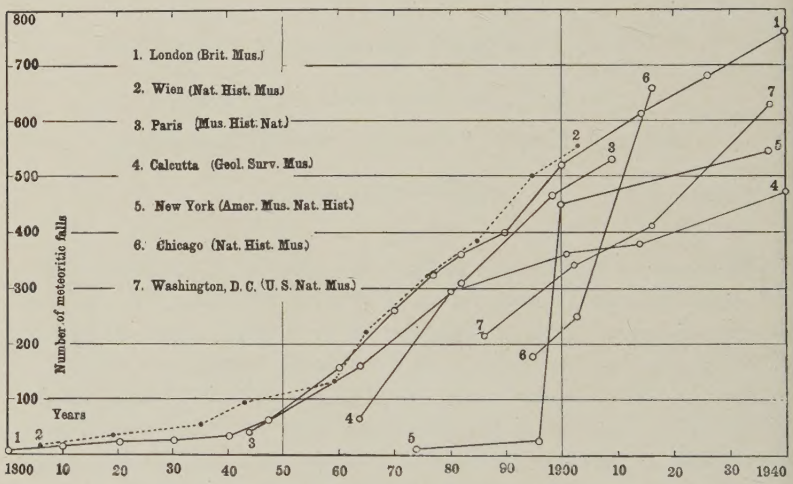

FIG. 1. Growth of meteorite collections, 1800–1940.

Formerly there were many more private collections of meteorites than at present, and Wülfing's idea of formulating exchange values was to help such collections and so stimulate the interest in and the investigation of meteorites. Many of these private collections have now been absorbed in the larger public collections, where they can be more permanently preserved, and with less danger of being lost, as has unfortunately happened with many unique specimens. Clearly this is the best plan in the case of the rarer falls and types.

The present bibliography, intended as a supplement to Wülfing, contains a few earlier references, not mentioned by him, to privately printed lists of private collections. With these and all other later lists a statement is given of the number of falls and when possible the total weight of material in each collection. Weights of individual specimens are usually stated in the catalogues but not always the total weight, and to add these up would be too laborious. The distinction often made

between 'falls' and 'finds' gives rise to some ambiguity, for 'finds' are only unobserved falls.

In addition to catalogues of collections, as at first planned, it has been thought useful to include some other relevant references later than Wülfing 1897. These include: general catalogues of meteorites; collective accounts of the meteorite falls in different countries, especially when they give information as to the depository of the material; and the all too few text-books on meteorites. For the more recent publications a reference is also added to Mineralogical Abstracts [M.A.].

The graph shows the growth of some of the more important meteorite collections from 1800 to 1940. The rocketing increase in the American collections, as compared with the European, is due to the absorption of large private collections.

Anderson (C.). A catalogue and bibliography of Australian meteorites, with census and taxonomy. Rec. Aust. Mus., 1913, vol. 10, no. 5, pp. 53–76. (46 falls.)

Astapovich (I. S.) Astapowitsch (I. S.) Астаповичъ (И. С.). A list of meteorites of the Soviet Union. Journ. Roy. Astron. Soc. Canada, 1938, vol. 32, pp. 195–196. (90 falls.) [M.A. 7–172.]

Ball (V.). Catalogue of the examples of meteoric falls in the museums of Dublin. Sci. Proc. Roy. Dublin Soc., 1882, vol. 3, pp. 298–301. (31 falls.)

Barnes (V. E.). Catalogue of Texas meteorites. Univ. Texas Publ., 1940, no. 3945, pp. 583–612. (70 falls.) [M.A. 8–59.]

Baumhauer (E. H. von). Collection de pierres et fers météoritiques du Professeur E. H. von Baumhauer . . . à Harlem, mars 1882. Harlem, 1882, 8 pp. (116 falls, 13½ kg.)

— Pierres et fers météoriques de la collection du Professeur E. H. von Baumhauer: suite du catalogue de mars 1882. Harlem, 1884, 4 pp. (64 falls.) (Also a sale catalogue by B. Stürtz, Bonn; most of the material going to the Hungarian National Museum, Budapest.)

Belgrade. Collection des météorites du musée de Belgrade. n.d., 3 pp. (59 falls.)

Bement (C. S.). Fourth rough list of meteorites. C.S.B., 1897, 27 pp. (413 falls, 412 kg.) (This collection acquired by the American Museum of Natural History, New York, in 1900.)

Berwerth (F.). Verzeichnis der Meteoriten im k.k. naturhistorischen Hofmuseum, Ende Oktober 1902. Ann. naturhist. Hofmus. Wien, 1903, vol. 18, pp. 1–90. (560 falls, 3313 kg.)

— Fortschritte in der Meteoritenkunde seit 1900. Fortsch. Min. Krist. Petr., 1911, vol. 1, pp. 257–284; 1912, vol. 2, pp. 227–258; 1913, vol. 3, pp. 245–272. [M.A. 1–96.]

Blattmann (S.) & Machatschki (F.). Stand der Tübinger Meteoritensammlung mit Ende 1937. Neues Jahrb. Min. Beil.-Bd., Abt. A, 1938, vol. 74, pp. 279–292. Correction: Zentralbl. Min., Abt. A, 1938, p. 382. (267 falls, 304 kg.) [M.A. 7–265.]

Blyth (T. R.) *v.* Fedden (F.).

Braun (—). Meteoriten-Sammlung des Freiherrn von Braun. Wien, 1884, 12 pp. (222 falls.)

Brauns (R.). Die Meteoritensammlung der Universität Bonn. Verh. Naturhist. Ver. Rheinlande u. Westfalens, 1926, vol. 83, pp. 160–188. (353 falls, 450½ kg.) [M.A. 3–252.]

Brezina (A.). The arrangement of collections of meteorites. Proc. Amer. Phil. Soc., 1904, vol. 43, pp. 211–247, 7 pls.

Brown (J. C.). A descriptive catalogue of the meteorites comprised in the collection of the Geological Survey of India, Calcutta (on August 1st, 1914). Mem. Geol. Surv. India, 1916, vol. 43, pp. 149–237. (379 falls.) [M.A. **1**–94.]

Bruhns (W.). Verzeichnis der Meteoriten des Mineralogischen und Petrographischen Institut der Universität Strassburg. Strassburg, 1903, 13 pp. (212 falls, 22½ kg.)

Brush (G. J.). Catalogue of meteorites in the Mineralogical collection of Yale College. 1869, 4 pp. (103 falls.)

Castillo (A. del). Catalogue descriptif des météorites (fers et pierres météoritiques) du Mexique. Paris, 1889, 15 pp., map. (27 falls.)

Cohen (E.). Verzeichniss der Meteoriten in der Greifswalder Sammlung am 1. Juli 1895. Mitt. Naturwiss. Ver. Neu-Vorpommern und Rügen, 1895, vol. 27, pp. 51–65. (143 falls, 8⅓ kg.)

— Ditto am 1. Januar 1901. Ibid., 1901, vol. 32 (for 1900), pp. 45–71. (281 falls, 14¾ kg.)

— Meteoritenkunde. Heft 2, Stuttgart, 1903, vii+302 pp. Heft 3, 1905, xvi+419 pp.

Coulson (A. L.). A catalogue of meteorites with special reference to Indian falls and to specimens in the Indian Museum, Calcutta, as to August 1st, 1939. Mem. Geol. Surv. India, 1940, vol. 75, 348 pp., 6 pls. (468 falls in Indian Mus., total known falls 1258.)

Daubrée (A.). Météorites du Muséum d'Histoire Naturelle de Paris au 15 décembre 1864. 4 pp. (160 falls.)

— Ditto au 31 mars 1868. 4 pp. (204 falls.)

— Guide dans la collection des météorites du Muséum d'Histoire Naturelle. Paris, 1882, 40 pp. (306 falls.)

Dewalque (G.). Catalogue des météorites conservées dans les collections belges. Ann. (Mém.) Soc. Géol. Belg. Liége, 1905, vol. 32, pp. M 15–M 19.

Di Fiore (O.). Le meteoriti del museo mineralogico della Università di Napoli. Boll. Soc. Nat. Napoli, 1930, vol. 41 (for 1929), pp. 68–71. (29 falls, 15¾ kg.) [M.A. **4**–416.]

Farrington (O. C.). Catalogue of the collection of meteorites, May 1, 1903. Field Mus. Chicago, 1903, Publ. 77, Geol. Ser., vol. 2, no. 2, pp. 79–124, 10 pls. (251 falls, 2289 kg.)

— Ditto. Ibid., 1916, Publ. 188, Geol. Ser., vol. 3, no. 10, pp. 231–312, 5 pls. (657 falls, 7566 kg.) [M.A. **1**–95.]

— Catalogue of the meteorites of North America, to January 1, 1909. Mem. National Acad. Sci. Washington, 1915, vol. 13, 513 pp. 4°, 36 pls. (247 falls.)

— Meteorites, their structure, compositions, and terrestrial relations. Chicago, 1915, x+223 pp.

Faura y Sans (M.). Meteorits caijuts a Catalonia. Butl. Cent. Excur. Catalunya, Barcelona, 1921, vol. 31, pp. 270–288, 4 pls. (10 falls.) [M.A. **2**–36.]

— Meteoritos caídos en la península Ibérica. Tortosa, 1922, 74 pp. Reprint of nine articles in 'Ibérica', 1922, vols. 17 and 18. (41 falls.) [M.A. **2**–86.]

Fedden (F.). Popular guide to the geological collections in the Indian Museum, Calcutta. No. 3, Meteorites. Calcutta, 1880, 49 pp. (290 falls.) Appendix by T. R. Blyth, Calcutta, 1901, 9 pp. (363 falls.)

Fernández Navarro (L.). Los meteoritos del museo de Madrid. Bol. R. Soc. Española Hist. Nat., 1923, vol. 23, pp. 224–233. (131 falls, 188¾ kg.) [M.A. **2**–260.]

Fletcher (L.). A guide to the collection of meteorites in the Department of Mineralogy in the British Museum (Natural History). London, 1881, 39 pp.; 1882, 40 pp. (361 falls.)

— An introduction to the study of meteorites, with a list of the meteorites represented in the collection. Mineral Department, British Museum (Natural History). Eleven editions, London, 1886–1914, 77 and 125 pp. (609 falls.) [M.A. **1**–145.]

Foote (W. M.). The Foote collection of meteorites. Meteorites. Philadelphia, 1912, part 2, pp. 27–61. (205 falls, 36 kg.)

Gordon (S. G.). Meteorites in the collections of the Academy of Natural Sciences of Philadelphia. Proc. Acad. Nat. Sci. Philadelphia, 1934, vol. 35 (for 1933), pp. 223–231. (85 falls.) [M.A. **6**–204.]

Greg (R. P.). Catalogue of the collection of meteorites belonging to R. P. Greg, Esq. Manchester, 1865, 8 pp. (224 falls.) (Greg's earlier collection acquired by the British Museum in 1860.)

Gregory (J. R.). Catalogue of the collection of meteorites of James R. Gregory, of London. London, 1889, 22 pp., with two undated addenda, 6 and 4 pp. (406 falls.) Other editions, 1901, 24 pp., and 1904, 20 pp. (Sold; the main portion to the Chicago Nat. Hist. Mus.)

Haidinger (W.). Die Meteoriten des k. k. Hof-Mineralien-Cabinetes. Six editions, Wien, 1859–65, each 4 pp. (137–220 falls.)

Haro (J. C.). Las meteoritas mexicanas. Generalidades sobre meteoritas y catálogo descriptivo de las meteoritas mexicanas. Bol. Inst. Geol. Mexico, 1931, no. 50, 88 pp., 40 pls. [M.A. **5**–158.]

Heide (F.). Die Meteoritensammlung der Technischen Hochschule zu Braunschweig. Jahresber. Ver. Naturwiss. Braunschweig, 1919, vol. 18 (for 1913–19), reprint 7 pp. (25 falls, 27½ kg.)

— Kleine Meteoritenkunde. Berlin, 1934, vii + 120 pp. (33 falls in Germany, map.) [M.A. **6**–9.]

— Fortschritte in der Meteoritenkunde. Fortsch. Min. Krist. Petr., 1937, vol. 21, pp. 225–275. [M.A. **10**–395.]

Hey (M. H.). Second appendix to the catalogue of meteorites, with special reference to those represented in the collection of the British Museum (Natural History). London, 1940, 136 pp. (758 falls in Brit. Mus. colln.; total known falls 1251.) [M.A. **7**–534.]

Hodge-Smith (T.). Australian meteorites. Mem. Austr. Mus. Sydney, 1939, no. 7. 84 pp. 19 pls. (84 falls.) [M.A. **7**–380.]

Högbom (A. G.). Verzeichniss über die Meteoriten des Mineralogischen Instituts an der Universität Upsala. Bull. Geol. Inst. Upsala, 1902, vol. 5 (for 1901), pp. 284–286. (86 falls.)

Horn (E.). Die Meteoritensammlung des Mineralogisch-Geologischen Instituts zu Hamburg. Jahrbuch Hamburg. Wiss. Anstalten, 1913, vol. 30, Beiheft 6, pp. 1–18, 2 pls. (146 falls, 748⅛ kg.)

Hovey (E. O.). Catalogue of meteorites in the collection of the American Museum of Natural History to July 1, 1896. Bull. Amer. Mus. Nat. Hist., 1896, no. 8, pp. 149–155. (26 falls, 36½ kg.)

Howard (K. S.). The Rochester collection of meteorites. Rochester, N.Y., 1909, 28 pp., 3 pls. (234 falls.)

Jimbō (K.). General note on Japanese meteorites. Beitr. Min. Japan, 1906, no. 2, pp. 30–52, 1 pl., map. (16 falls.)

Kantor (M.). Guía y catálogo de la colección de los meteoritos existentes en el Museo de La Plata con especial mención de los meteoritos Argentinos. Rev. Museo La Plata, 1920, vol. 25, pp. 97–125, 3 pls. (31 falls, incl. 8 Argentina.) [M.A. **1**–146.]

Klein (C.). Die Meteoritensammlung der Königlichen Friedrich-Wilhelms Universität zu Berlin am 5. Februar 1903. Sitz.-ber. Preuss. Akad. Wiss. Berlin, 1903, pp. 139–172. (380 falls, 233 kg.)

— Ditto am 21. Januar 1904. Ibid., 1904, pp. 114–153. (379 falls, 233 kg.) Supplementary list, ibid., 1904, pp. 978–983. (470 falls, 255 kg.)

[Konig (C.)]. Meteorites in the British Museum, 1847. 3 pp. Reprinted on 4° paper from pp. 54–57 of the 52nd edition of Synopsis of the contents of the British Museum. (59 falls.)

Krinov (E. L.). Short catalogue of U.S.S.R. meteorites to July 1, 1945. (Russian.) Astron. Journ. Soviet Union, 1945, vol. 22, no. 5, pp. 303–311. (113 falls.) [M.A. **9**–297.]

Kulik (L. A.). Additions to the meteorite collection of the Academy of Sciences, Moscow, during 1934–39.

(Russian.) Meteoritica, Moscow, 1941, vol. 1, pp. 73–123. (29 falls.) [M.A. **9**–294.]

Labat (A.). Guide dans la collection des météorites avec le catalogue des chutes représentées au muséum. Muséum d'Histoire Naturelle, Paris [8th edition], 1909, 62 pp. (532 falls, 2258½ kg.)

Lacroix (A.). Les météorites tombées en France et dans ses colonies et conservées au Muséum national d'Histoire Naturelle, avec remarques sur la classification des météorites. Bull. Mus. Hist. Nat. Paris, 1927, vol. 33, pp. 411–455. Supplement for colonies, ibid., 1931, ser. 2, vol. 3, pp. 131–134. [M.A. **3**–534, **5**–88.]

Latteux (—). Catalogue de la [sa] collection de météorites. Paris, 1913, 30 pp.

Leonard (F. C.). A catalog of provisional coördinate numbers for the meteorite falls of the world. Univ. New Mexico Publ. Meteoritics, 1946, no. 1, 69 pp. (1347 falls.) [M.A. **10**–171.]

Levinson-Lessing (F.). Catalogue de la collection de météorites de l'université impériale de Iourie (Dorpat). Dorpat, 1897, 8 pp. Extract from Acta Univ. Dorpat, 1897, vol. 5, no. 2. (170 falls, 58½ kg.) Earlier lists by C. Grewingk, 1864–82.

Ludlam (H.). Ludlam–Nevill collection of meteorites in the possession of H. Ludlam, 174 Piccadilly, London. 11 pp. n.d. (230 falls.) Bequeathed in 1880 to the Museum of Practical Geology, Jermyn Street, now the Geological Survey Museum, South Kensington. *v.* Nevill.

Mauroy (A. C. de). Musée de Troyes (Aube), catalogue des météorites au 1er novembre 1886. Troyes, 1886, 4 pp. (56 falls.)

— Catalogue de la collection spéciale de météorites réunie par A. C. Marquis de Mauroy. Wassy, 1909, 39 pp. (381 falls.)

— Catalogue de la collection de météorites de l'observatoire du Vatican. Roma, 1913, 53 pp., 4°, 7 pls. (156 falls.)

Merrill (G. P.). Handbook and descriptive catalogue of the meteorite collections in the United States National Museum, 1916, Bull. 94, 217 pp., 41 pls. (412 falls, including the C. U. Shepard, Jr., collection.) A later total of 635 falls is mentioned in Rep. U.S. Nat. Mus., 1938, for 1937, p. 47. [M.A. **1**–94.]

Meunier (S.). Guide dans la collection de météorites avec le catalogue des chutes représentées au muséum. Muséum d'Histoire Naturelle, Paris, 1898, [7th edition], 118 pp. (466 falls.)

Michel (H.). Fortschritte in der Meteoritenkunde seit 1900. Fortsch. Min. Krist. Petr., 1922, vol. 7, pp. 245–326. [M.A. **2**–32.]

Millosevich (F.). Le meteoriti del museo mineralogico dell' università di Roma. Roma, 1928, 38 pp. (190 falls.) [M.A. **4**–117.]

Minneapolis, University of Minnesota. Catalogue of the meteorites in the university collection, with references to the literature describing them. Geol. Nat. Hist. Surv. Minnesota, 1892, 19th Ann. Rep. for 1890, pp. 170–192. (58 falls.)

Neumann (W. M.). Meteoriten-Katalog der Neumann'schen Sammlung. Graz, 1902, 10 pp. (225 falls.)

Nevill (W.). Catalogue of meteorites being the collection of William Nevill, F.G.S., Godalming, Surrey. 1867, 4 pp., 8° (187 falls); 1872, 4 pp., 8° (226 falls). Also two undated lists, 3 pp., 4°. *v.* Ludlam.

Nininger (H. H.). Our stone-pelted planet. A book about meteors and meteorites. Boston & New York, 1933, xxv+237 pp. [M.A. **5**–400.]

— The Nininger collection of meteorites. Mines Mag. Colorado School of Mines, 1933, vol. 23, no. 8, pp. 6–9, 12; and two reprints with slight alterations. (177 falls.) [M.A. **5**–405.]

Nordenskiöld (A. E.). Förteckning på meteoriter i Riksmusei mineralogiska samlingar. Öfversigt K. Vetenskaps-Akad. Förhandl., Stockholm, 1870, pp. 39–48. (127 falls.)

Oldham (T.). Catalogue of the specimens of meteoric stones and meteoric

irons in the museum of the Geological Survey, Calcutta. Three lists 1863–67, 3 and 9 pp. (64–247 falls.)

Oliveira (E. de). Collecções de meteoritos do Museu Nacional, do Serviço Geológico e Mineralógico do Brasil [Rio de Janeiro] e da Escola de Minas [Ouro Preto]. Ann. Acad. Brasil. Sci., 1931, vol. 3, pp. 33–56, 3 pls. [M.A. **5**–14.]

Palache (C.). Catalogue of the collection of meteorites in the Mineralogical Museum of Harvard University. Proc. Amer. Acad. Arts & Sci., 1926, vol. 61, no. 6, pp. 151–159. (351 falls, 1657 kg.) [M.A. **3**–252.]

Pohl (J. J.). Katalog einer Sammlung von Meteorsteinen und Meteoreisen aus dem Nachlasse des . . . J. J. Pohl. Wien, 1901, 16 pp.

Prior (G. T.). Catalogue of meteorites with special reference to those represented in the collection of the British Museum (Natural History). London, 1923, 206 pp. Appendix, 1927, 48 pp. (2nd Appendix *v.* Hey.) [M.A. **2**–97, **3**–463.]

— A guide to the collection of meteorites with an alphabetical list of those represented, Mineral Department, British Museum (Natural History). London, 1926, 43 pp. (680 falls, 6086 kg.) [M.A. **3**–463.]

Rath (G. vom). Die Meteoriten des naturhistorischen Museums der Universität Bonn. Bonn, 1875, 24 pp. (63 falls.)

Reeds (C. A.). Catalogue of meteorites in the American Museum of Natural History as of October 1, 1936. Bull. Amer. Mus. Nat. Hist., New York, 1937, vol. 73, pp. 517–672. (546 falls.)

Schreiter (R.). Die Meteoriten des Kgl. Mineralogischen Museum in Dresden. Sitz.-ber. Naturwiss. Gesell. Isis, Dresden, 1912, for 1911, pp. 58–75. (162 falls.)

Schweder (J.). Meteoritensammlung des Naturforscher-Vereins zu Riga. Korr.-bl. Naturf. Ver. Riga, 1912, vol. 55, pp. 63–65. (42 falls, 5 kg.)

Shepard (C. U.) [1804–1886]. Catalogue of the meteoric collection of Charles Upham Shepard deposited in the Wood's Building, Amherst College, Mass. Amherst, 1872, 8 pp. (239 falls, 1200 lb.) Other lists in 1851–64.

Shepard (C. U., Junior) [1842–1915]. Meteoric collection of Charles Upham Shepard, Jr., Charlestown, S.C. Charlestown, 1881, 4 pp. with 2 overprinted addenda. (150 falls.) (Bequeathed to U.S. Nat. Mus. Washington, D.C., 1915.)

Sigmund (A.). Die Meteoritensammlung des steierm. Landesmuseum „Joanneum" in Graz. Jahresber. Steierm. Landesmus. Graz, 1927, vol. 113–115 (for 1924–26), reprint 8 pp. (44 falls.) [M.A. **3**–465.]

Silberrad (C. A.). List of Indian meteorites. Min. Mag., 1932, vol. 23, pp. 290–304, 1 pl. (map).

Simashko (Y. I.) Siemaschko (J. de) Симашко (Ю). Four lists in French, German, and Russian, 1885–91. (374 falls.) (Collection now in Chicago Nat. Hist. Mus.)

Smith (J. L.). Catalogue of meteorites in the collection of J. Lawrence Smith, Louisville, Ky., U.S.A., January 1, 1876. 6 pp. (Acquired by Harvard University in 1883.)

Story-Maskelyne (N.). Catalogue of the collection of aërolites [meteorites] exhibited in the Mineral Department of the British Museum. Six editions, 1860–77, 4 and 8 pp. (156–321 falls.)

Tassin (W.). Descriptive catalogue of the meteorite collection in the United States National Museum to January 1, 1902. Rep. U.S. Nat. Mus., 1902, for 1900, pp. 671–698, 3 pls. (348 falls.)

Ussing (N. V.). List of meteorites represented in the collection, October 1, 1905, Mineralogical and Geological Museum of the University. Copenhagen, 1905, 12 pp. (174 falls.)

Vibraye (P. de). Catalogue des minéraux et météorites composant la collection de feu M. le Marquis P. de Vibraye. Paris, 1897. Sale catalogue, lots 941–1024.

Vidal (N.). Meteoritos Brasileiros. Bol. Mus. Nac. Rio de Janeiro, 1936,

vol. 12, nos. 3–4, pp. 91–109, 8 pls. [M.A. **8**–376.]

Vrba (K.). Meteoritensammlung des Museums des Königreiches Böhmen in Prag. Three editions, 1897, 1904, 1914. (79–255 falls.)

— Sbírka meteoritů v museu království Českého v Praze koncem r. 1913. Praha, 1914, 21 pp. (255 falls, 192½ kg.)

Ward (H. A.). Catalogue of the Ward-Coonley collection of meteorites. [2nd edition], Chicago, 1904, 125 pp. 10 pls. (603 falls, 2495½ kg.) (Collection now in Chicago Nat. Hist. Mus.)

Washington (H. S.). Catalogue of the collection of meteorites in the Peabody Museum of Yale University. Amer. Journ. Sci., 1897, ser. 4, vol. 3, pp. 83–87. (201 falls, 1374 kg.)

Watson (F. G.). Between the planets. Philadelphia, 1941 (London, 1947), iii+222 pp. [M.A. **10**–166.]

Weil (R.) & Siat (A.). Catalogue de la collection de météorites de l'Institute de Minéralogie et Pétrographie de l'Université de Strasbourg. Strasbourg, 1947, 62 pp. (278 falls, 41¼ kg.) [M.A. **10**–395.]

Wöhler (F.). Die Meteoriten in der Universität-Sammlung zu Göttingen. Four editions, 1864–73. (139–200 falls.)

Yamamoto (I.). Preliminary list of meteorites in Japan. Bull. Kwasan Observatory, Kyoto Univ., 1935, vol. 4, no. 306, 6 pp. [M.A. **7**–173.]

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Washington, D.C., *v.* Merrill, Shepard, Tassin
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The densest and the least dense packings of equal spheres.

By Sidney Melmore, B.Sc.

[Read June 24, 1948.]

The densest packings.—Of the results which have so far been achieved by study of the packing of equal spheres one of the most remarkable, both by reason of its simplicity and of its fundamental importance, was that announced by Barlow in 1883.[1] He called attention to the fact that equal spheres can be most densely packed in two ways, one possessing cubic symmetry and the other hexagonal (fig. 1).

Already in 1862 Tait[2] had investigated the piling of marbles of equal size and had noticed that 'there are two obvious ways of constructing the layers, and two of applying layer to layer': nevertheless his two densest arrangements are in fact identical. He saw that the cubic structure could be begun either upon a square base or a triangular base but failed to perceive the possibility of the hexagonal arrangement.

And even after Barlow announced his discovery, A. G. Greenhill[3] dealing in 1889 with the piling of spherical shot concluded that 'Whether we begin piling the shot in horizontal layers, in triangular order or in square order, the internal molecular arrangement of the spheres is the same'.

It was also in 1889 that Kelvin[4] dealt with the densest packing of equal spheres in connexion with his development of Boscovich's theory of the constitution of matter. While admitting that 'Mr. Barlow, so far as I know, was the first to show a cubic part of the close-packed homogeneous assemblage of equal globes', he declined to recognize the hexagonal structure as a homogeneous assemblage. But this came about through his adhering to a too-restricted definition of homogeneity.

In 1898 Barlow[5] took up the subject of the densest packing of unequal spheres. 'I may say', he remarks, 'that my general principle for getting closest-packing of the spheres is to produce a maximum number of

[1] W. Barlow, Nature, London, 1883, vol. 29, p. 186.

[2] P. G. Tait, Proc. Roy. Soc. Edinburgh, 1862, vol. 4, p. 535.

[3] A. G. Greenhill, Nature, London, 1889, vol. 40, p. 10.

[4] W. Thomson, Proc. Roy. Soc. Edinburgh, 1890, vol. 16, p. 693.

[5] W. Barlow, Proc. Roy. Dublin Soc., 1898, n. ser., vol. 8, p. 527 (preprints dated 1897).

contacts, so as to diminish, as far as possible, the amount of interstitial space.' In the case of equal spheres, it is taken as axiomatic that they are most densely packed when each is in contact with twelve others. He then goes on to remark that 'It is evident that twelve contacts for each sphere can be attained in a variety of different ways. There are two and two only, which give homogeneity of structure.'

However, by 1907 he had gained further light on the matter, and having once more described the arrangements shown in fig. 1, he adds:

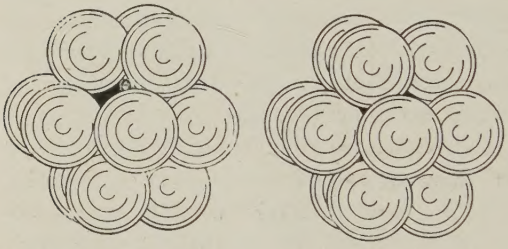

Fig. 1.

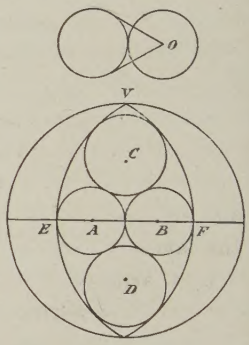

Fig. 2.

'The two assemblages above described are equally close packed and can, by combination or admixture, give rise to other equally close-packed homogeneous assemblages.'[1]

The question as to how many such closest-packed homogeneous mixtures there might be was left by Barlow incompletely answered; but it has recently been found that there are four.[2] There are thus all together six homogeneous structures possessing 12-point contact and having therefore the same density[3] of 0·74048. . .

It has lately been remarked as a curious fact that although it is obviously true that equal spheres are most densely packed when each is in contact with twelve, nobody has yet succeeded in proving it. Several persons have shown that it is true when the sphere-centres are at the corners of a parallelepiped, the earliest so far as I know being Kelvin in the paper already cited. But the problem still remains to be considered free from such restrictions.

[1] W. Barlow and W. J. Pope, Journ. Chem. Soc. London, 1907, vol. 91, p. 1158.

[2] S. Melmore, Nature, London, 1947, vol. 159, p. 817.

[3] By *density* is meant the ratio of the total volume of the spheres in a lattice cell to the whole volume of the cell.

It might be thought that the property of dilatancy[1] is in itself a satisfactory proof: for if any distortion of normal piling with 12-point contact results in an increase in the overall volume, and therefore a diminution of density, it follows that 12-point contact is the condition for maximum density. But setting this aside, we may approach the matter in another way:

The upper part of fig. 2 represents two equal spheres (radius = 1) in contact: from O, the centre of one sphere, project the other on to it. The projection will be a small circle with an angular diameter of 60°: the area of the small circle is therefore $0{\cdot}268\pi$.

In place of the question: What is the greatest number of equal spheres that can be brought into contact with another of the same size?, we may now ask: What is the greatest number of non-intersecting small circles (diameter = 60°) that can be inscribed on a sphere?

In the stereographic projection, fig. 2, the four small circles are equal and have angular diameters of 60°: two, with their poles at A and B respectively, are in contact. A third, C, will be most closely packed when it is in contact with the first two; and again, a fourth, D, will be most closely packed in like circumstances. Through A and B draw a great circle intersecting the small circles A and B in E and F. Through E and F draw secondaries to this great circle. Then the angle of the lune $VEV'F$ is equal to the arc $EF = 120°$. So the area of the lune is one-third the area of the whole sphere, that is to say, its area is $\frac{4}{3}\pi$.

The sum of the areas of the four small circles is $4\times0{\cdot}268\pi = 1{\cdot}072\pi$. The residual area is therefore $(1{\cdot}333-1{\cdot}072)\pi = 0{\cdot}261\pi$, which is less than the area of one small circle. So not more than four circles can be accommodated within the lune, and therefore not more than twelve on the whole surface of the sphere. Hence not more than twelve equal spheres can be brought into contact with another of the same size.

Taking another view of the problem: It has been proved[2] that the closest packing of equal circles in a plane is that in which each circle is in contact with six, fig. 3. Let the middle circle rotate about a diameter so as to generate a sphere. We may then inquire: What is the greatest number of planes through the centre of this sphere upon which a like set of neighbouring circles can be inscribed, having regard to the symmetry?

[1] Osborne Reynolds, Phil. Mag., 1885, ser. 5, vol. 20, p. 469. The sub-mechanics of the universe, Cambridge, 1903. Rede Lecture, Cambridge, 1902.

[2] B. Segre and K. Mahler, Amer. Math. Monthly, 1944, vol. 51, p. 261. But I have not seen this paper.

There is an axis of symmetry normal to the plane through the centre of the middle circle, which may be regarded as hexagonal or as trigonal. If hexagonal, then there can be only one plane: if trigonal, there may be four, but no more. These planes are parallel to the faces of the octahedron, and are represented by the great circles in the stereographic projection, fig. 4, where three of them are projected on the plane of the fourth.

The great circles may be thought of as passing through the centres of the six circles in their respective planes. It follows from considerations

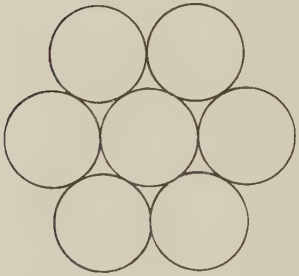

Fig. 3.

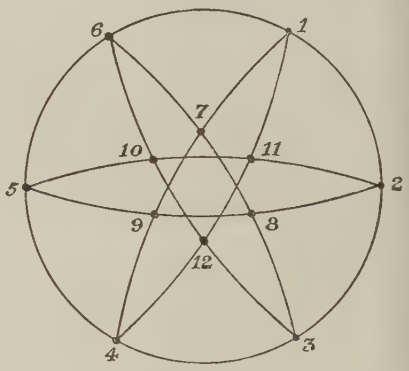

Fig. 4.

of symmetry that the centres of these latter circles lie at the intersections of the great circles (numbered in the figure); and since the great circles intersect in pairs, the total number of circles in contact with the central sphere is $\frac{4\times 6}{2} = 12$.

It is easily seen that all the arc-segments joining the numbered points of intersection are arcs of 60°: therefore when all the twelve circles each rotate about a diameter they will generate spheres touching the central sphere and also touching their other neighbours.

The least dense packings.—Although the study of the most open packings of equal spheres is of comparatively recent date, some of the results have already found application in the elucidation of the structure of ionic minerals[1] and of the assemblages built up by ultra-microscopic dust particles.[2] The problem of the most open packing was first propounded by H. Heesch and F. Laves in 1933.[3]

[1] H. W. Fairbairn, Bull. Geol. Soc. Amer., 1943, vol. 54, p. 1305. [M.A. 9–41.]
[2] H. Heywood, Journ. Imp. Coll. Chem. Eng. Soc., 1946, vol. 2.
[3] H. Heesch and F. Laves, Zeits. Krist., 1933, vol. 85, p. 443. [M.A. 5–342.]

The principal conditions they impose are that: (i) the structure is composed of congruent spheres, (ii) it is continuous, (iii) either sphere of a pair can be transformed into the other by symmetry operations, (iv) the lines joining the points of contact of successive spheres pass through the centres of the spheres, thus ensuring the stability of the structure. (It follows from this condition that when a sphere is in contact with no more than three others, the four sphere-centres must be coplanar.)

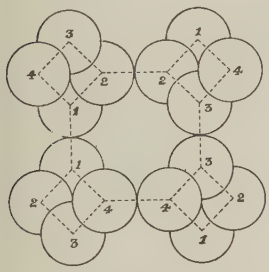

Fig. 5.

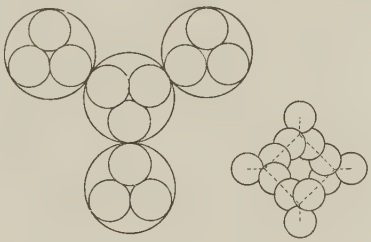

Fig. 6.

Condition (iii) is of some practical importance. It means that the whole structure can be developed by applying symmetry operations to a single sphere. If, on the other hand, we operate upon a group of spheres, structures can be developed which are even less dense than those found by Heesch and Laves.[1] However, in what follows, this condition is retained. Of the nine assemblages described by these authors, it is here necessary to consider only two; both possess cubic symmetry and are non-self-reflexible.

The nature of the first is indicated by the ground plan of the left-handed form, fig. 5. The spheres are arranged round tetragonal screw-axes having a pitch angle of 45°, and there are digonal axes of rotation between the screws. Each sphere makes contact with three others, and the lines of centres from any one sphere to its three neighbours make angles of 120°. This structure has a density of 0·185 . . .

From this assemblage Heesch and Laves derive another by applying an ingenious three-for-one substitution, the nature of which will be at once evident from the diagram in the left-hand half of fig. 6. When this is done, the tetragonal screws of fig. 5 become 2-point tetragonal screws with a connecting sphere between. One such element of the new structure is shown in the right-hand half of fig. 6.

[1] S. Melmore, Nature, London, 1942, vol. 149, p. 669. [M.A. **8**-344, **9**-139.]

The structure thus derived has a density of 0·056,[1] and is the most open described by Heesch and Laves. The opinion has been expressed[2] that this may perhaps be the most open structure possible (under condition (iii)), but till now no proof has been forthcoming.

The following considerations are based upon Barlow's conception of *singular points*.[3] These are concisely defined in the Dublin paper (footnote to p. 627): 'Singular points in a homogeneous structure are points which occupy specially symmetrical situations, and so form point-

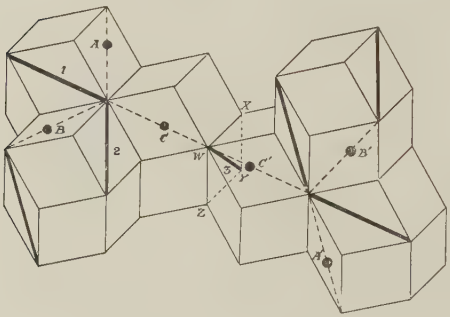

Fig. 7.

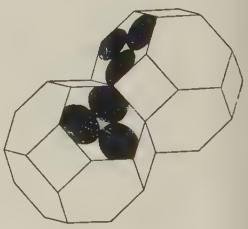

Fig. 8.

systems containing fewer points than ordinarily; they lie on axes of rotation or on planes of symmetry, or on both'; but the paper in the Zeitschrift must be consulted for the full exposition.

It is clear then, that if we are to fill a given space with a homogeneous arrangement of as few spheres as possible, the sphere-centres will be singular points. Following Barlow's train of thought (Zeitschrift, pp. 60–62) it is evident that if there are to be as few singular points as possible, then structures with a principal axis of rotation are ruled out, and we are left with the consideration of digonal axes only.

To visualize the position of all the possible digonal axes: Let space be partitioned into rhombic dodecahedral cells: then the digonal axes will be represented by the normals joining opposite faces.[4] They lie in

[1] The value is thus given by Heesch and Laves. I have carried the calculation farther, using 7-figure logarithms, with the result 0·055515 . . .

[2] W. Nowacki, Homogene Raumteilung und Kristallstruktur. Zürich, 1935, p. 48.

[3] W. Barlow, Zeits. Kryst. Min., 1894, vol. 23, p. 1; Proc. Roy Dublin Soc., 1898, n. ser., vol. 8, p. 527.

[4] The particular normals which are the digonal axes of the extended structure lie in the surface of the cells as indicated in fig. 7, which represents one of the models exhibited when the paper was read.

possible planes of reflection, and other symmetry elements are also potentially available. As will appear immediately, the question which and how few of all these potential elements are necessarily operative is automatically answered by the conditions of the problem.

In fig. 7, let A be a sphere-centre located on a digonal axis;[1] then the axis *1* will develop from it the point B. Axis *2* will carry B to C. We now have three sphere-centres A, B, C, defining a plane. Now by condition (iv) a fourth centre must lie in this plane and also on the diameter (produced) of one of the existing spheres. C' is therefore a possible position. To carry C to C', two courses are open: either C may be reflected across the plane $WXYZ$, or the digonal axis no. *3* (i.e., WY) may be employed. But the first process leads merely to the development of a single sheet of spheres. On the other hand, by the operation of the digonal axis no. *3*, C is carried to C', A to A', and B to B', so that a 3-dimensional distribution of sphere-centres comes into being.

The structure developed by repetition of these rotations is identical with that of Heesch and Laves, having the density 0·056. (The points B, C, C', A', for instance, are part of a 2-point tetragonal screw such as is shown in plan in fig. 6.) This structure, first discovered by Heesch and Laves, is then the most open possible under the given conditions.

It was necessary for the purposes of proof to employ digonal axes only; but now that this is done we see that of all the potential digonal axes those actually used are themselves distributed around threefold axes of rotation, and the sphere-centres are consequently similarly related.

As the normals to the faces of the octahedron are threefold axes of rotation, a conveniently compact model of this structure can be made by preparing several equal truncated octahedra, inscribing three circles (to represent spheres) on one hexagonal face of each octahedron, and fixing them together so that each is connected to four others at faces tetrahedrally related. Two such truncated octahedra are shown in fig. 8.

[1] In order that the spheres shall be in contact, A must bisect the long face diagonal in the ratio 0·758 : 0·875.

Two olivines from South African melilite-basalts.

By Morna Mathias, M.A., Ph.D.

Geology Department, University of Cape Town.

[Read October 7, 1948.]

Introduction.—The separation and analysis of the olivine phenocrysts from the Spiegel river and Klaasvoogds melilite-basalts was undertaken in order to ascertain whether the olivines contain significant amounts of Ca_2SiO_4 in their constitution in view of the fact that the closely allied rock-types, alnöite (Bowen, 1922) and the basalt from Shannon Tier, Tasmania (Tilley, 1928), are known to contain monticellite, and that Taljaard (1936) has tentatively identified monticellite in one of the melilite-basalts from the Sutherland district, Cape Province.

The Spiegel river melilite-basalt from the Riversdale district of the Cape Province was first described by Corstorphine (1898). Petrographic descriptions of the rock have been given by Rogers and Schwarz (1898), Rogers and du Toit (1903), Rogers (1905), Wagner (1914), du Toit (1926), Taljaard (1936), and Holmes (1936). Partridge (1934) examined some of the minerals spectroscopically and recorded the presence of two grains of anatase in the heavy residue. The latest petrographic description, that by Holmes (1936), has been supplemented only in respect of the optical, chemical, and physical properties of the olivines. The author agrees with Taljaard (1936) in recording a complete absence of peg-structure in the melilites examined, but finds that the optical properties of the olivines differ somewhat from those he gives. It should be pointed out, however, in this connexion, that melilite-basalts are notoriously variable in their composition and that it is therefore quite possible that samples taken from different parts of the outcrop should show different concentrations and optical properties of their constituents.

The Klaasvoogds melilite-basalt from the farm Goedemoed Annexe in the Robertson district of the Cape Province was first discovered by M. S. Taljaard (1936), and his description of the rock is the only one as yet published. The writer has found some interesting variations in the optical properties of the olivines, and records for the first time the presence of nepheline, leucite, analcime, apatite, and zircon.

The present research includes a more detailed description of the

Klaasvoogds rock as well as chemical and optical data on the olivines from Spiegel river and Klaasvoogds.

Methods.—The olivines were separated for analysis by heavy liquid and magnetic methods, followed by hand-picking. 2V determinations were carried out on a four-circle universal stage and the refractive indices were measured by the immersion method using a Tully refractometer and sodium-light. Specific gravity was measured in alcohol by the pyknometer method.

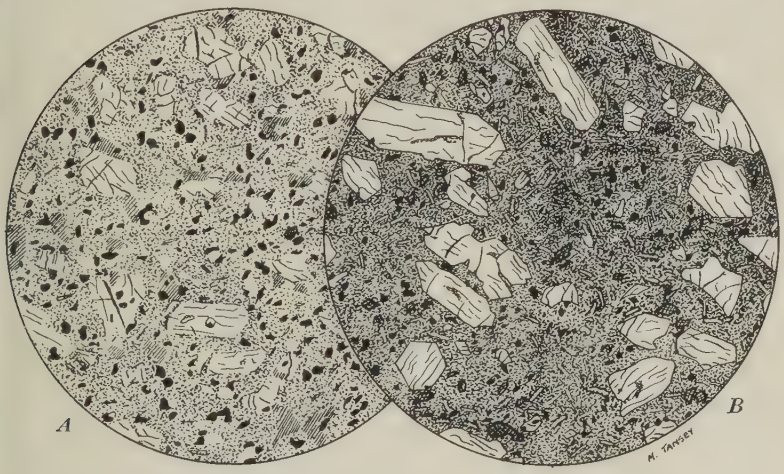

Fig. 1. *A*. Klaasvoogds melilite-basalt (×22 diam.). *B*. Spiegel river melilite-basalt (×22 diam.).

General petrography of the Klaasvoogds melilite-basalt.—In hand-specimen the melilite-basalt from Klaasvoogds can be distinguished readily from that of Spiegel river by the less compact nature of the groundmass. It is a porphyritic greenish-black rock containing phenocrysts of olivine measuring up to 10×6 mm. in size. The olivine is usually very fresh, but the larger crystals occasionally show complete serpentinization. In thin section (fig. 1) the olivine is colourless, rarely shows alteration, and has an average grain-size of 0·4×0·2 mm. Brachypinacoidal cleavage is frequently seen. The olivine may enclose magnetite; while biotite, clinopyroxene, and perovskite have occasionally formed along cracks within the crystals. The groundmass is composed of microporphyritic crystals of magnetite, melilite, perovskite, ±nepheline, set in a matrix composed of predominantly lath-like clinopyroxene,

magnetite, perovskite, melilite, interstitial biotite, nepheline, and colourless isotropic material which it was not possible to identify in section. The proportion of nepheline and biotite present in the rock is variable. Melilite is optically negative and generally builds rectangular or hour-glass-shaped crystals elongated parallel to the base. It sometimes shows mechanical zoning of inclusions. The basal parting is rarely observable though prismatic cleavage is occasionally seen. Clinopyroxene is pale brown in colour, and has a maximum extinction angle of 44° and γ 1·724.

After separation in bromoform the light crop yielded nepheline (α 1·532, γ 1·536); leucite (n 1·508); analcime (n 1·486), and apatite (α 1·633). Analcime was identified by its refractive index and the negative results to microchemical tests for sodalite, nosean, and haüyne.

Optical and chemical data for the olivines.—Two distinct sets of optical properties were found for the olivines in the Klaasvoogds melilite-basalt. The first, (A) values, were yielded by the samples collected for separation and analysis of the olivines. Later, samples were kindly collected by a student, Mr. E. S. W. Simpson, and these yielded similar values in some specimens and dissimilar values in others. The latter are indicated (B). It is, unfortunately, impossible to state with accuracy from which parts of the outcrop the two collections were made. All that can be said with certainty is that the basalt is variable in character. This is borne out not only by the difference in properties of the olivines, but by the considerable variation in the proportions of biotite, melilite, and nepheline.

TABLE 1. Chemical and optical data.

Olivine from the Spiegel river melilite-basalt. (Analyst, Geochemical Laboratories.)

Analysis.		100 %.	Atomic ratios.		Atomic ratio to 4O.
SiO_2	39·12	39·24	Si^{****}	0·654	0·947	0·95
TiO_2	0·09	0·09	Ti^{****}	0·001	0·001	
Al_2O_3	0·58	0·58	Al^{***}	0·011	0·016	
Fe_2O_3	1·69	1·70	Fe^{***}	0·021	0·031	
FeO	10·76	10·80	Fe^{**}	0·150	0·224	2·03
MnO	0·16	0·16	Mn^{**}	0·002	0·003	
MgO	46·51	46·67	Mg^{**}	1·167	1·739	
CaO	0·48	0·48	Ca^{**}	0·009	0·013	
Na_2O	0·15	0·15	O^{**}	2·685	4·000	4·00
K_2O	0·06	0·06				
P_2O_5	0·07	0·07				
H_2O+ ...	0·21	100·00				
H_2O- ...	0·07					
	99·95					
Sp. gr. ...	3·33					

Formula: $(Mg,Fe'',Ca,Mn)_2[SiO_4]$

$Fo_{89}Fa_{11}$

α 1·656, β 1·674, γ 1·695, $2V\gamma$ 89°.

TABLE I (*cont.*).

Olivine from Klaasvoogds. (Analyst, Geochemical Laboratories.)

	Analysis.	100 %.	Atomic ratios.		Atomic ratio to 4O.
SiO_2	37·33	37·43			
TiO_2	0·09	0·09	$Si^{\cdots\cdot}$	0·624	0·979 0·98
Al_2O_3	0·18	0·18	$Al^{\cdots}$	0·003	0·005
Fe_2O_3	1·60	1·61	$Fe^{\cdots}$	0·020	0·031
FeO	21·58	21·64	$Fe^{\cdot\cdot}$	0·300	0·471 2·02
MnO	0·27	0·27	$Mn^{\cdot\cdot}$	0·004	0·006
MgO	38·13	38·23	$Mg^{\cdot\cdot}$	0·956	1·500
CaO	0·38	0·38	$Ca^{\cdot\cdot}$	0·007	0·011
Na_2O	0·03	0·03	$O^{\cdot\cdot}$	2·550	4·000 4·00
K_2O	0·05	0·05	Formula: $(Mg,Fe'',Ca,Mn)_2[SiO_4]$		
P_2O_5	0·09	0·09	$Fo_{76}Fa_{24}$		
H_2O+... ...	0·17	100·00	(A): α 1·683, β 1·704, γ 1·722, 2Vα 85°.		
H_2O-... ...	0·04		(B): α 1·657, β 1·672, γ 1·692, 2Vγ 89°.		
	99·94				
Sp. gr. . .	3·53				

TABLE II. Comparative chemical analyses.

	1.	2.	3.	4.	5.	6.	7.	A.	B.	C.
SiO_2 ...	39·12	37·33	40·33	40·27	40·87	38·11	40·84	36·15	36·95	37·13
TiO_2 ...	0·09	0·09	0·08	—	nil	trace	0·04	2·30	4·59	3·61
Al_2O_3 ...	0·58	0·18	0·42	2·21	0·57	nil	0·19	15·18	7·85	10·58
Fe_2O_3 ...	1·69	1·60	1·13	—	trace	0·15	0·13	4·87	4·78	2·00
FeO ...	10·76	21·58	10·39	7·14	6·77	31·48	8·18	9·11	8·70	10·43
MnO ...	0·16	0·27	0·11	—	trace	0·22	0·17	0·33	0·20	0·26
MgO ...	46·51	38·13	47·20	48·61	50·84	30·50	50·27	13·63	15·87	19·12
CaO ...	0·48	0·38	0·16	—	nil	0·02	—	11·40	13·60	13·02
Na_2O ...	0·15	0·03	0·12	—	—	—	—	2·42	2·32	1·32
K_2O ...	0·06	0·05	0·06	—	—	—	—	1·81	2·04	0·51
P_2O_5 ...	0·07	0·09	—	—	—	—	—	0·26	0·83	nil
H_2O+ ...	0·21	0·17	—	1·10	0·81	—	<0·37	1·95	1·64	0·83
H_2O- ...	0·07	0·04	—			—		0·37	0·49	0·37
&c.* ...	—	—	—	—	—	—	0·19	0·65	0·39	0·47
	99·95	99·94	100·00	99·33	99·86	100·48	100·38	100·43	100·25	99·65
2V ...	89°(+)	85°(−)	—	—	—	79°(−)	90° ca.	—	—	—
α ...	1·656	1·683	—	—	—	1·710	1·649	—	—	—
β ...	1·674	1·704	—	—	—	1·733	1·666	—	—	—
γ ...	1·695	1·722	—	—	—	1·748	1·684	—	—	—
Sp. gr. ...	3·33	3·53	—	—	—	—	3·3	—	—	—

1, Olivine, Spiegel river. 2, Olivine, Klaasvoogds. 3, Olivine (average), Hawaii (Daly, 1944). 4, Olivine, kimberlite, de Beers mine, South Africa (Wagner, 1914). 5, Olivine, kimberlite, Klipfontein mine (Wagner, 1914). 6, Olivine, Skaergaard, Greenland (Deer and Wager, 1939). 7, Olivine, California (Hawkes, 1946). A, Melilite-basalt, Spiegel river (Rogers and du Toit, 1903). * Cr_2O_3 0·10, BaO 0·06, SO_3 0·49. B, Melilite-basalt, Spiegel river (Holmes, 1936) *Cr_2O_3 0·03, NiO 0·04, ZrO_2 0·04, F 0·05, V_2O_3 0·04, SrO 0·04, BaO 0·09, CO_2 0·06. C. Melilite-basalt, Klaasvoogds (Taljaard, 1936) * CO_2 0·47.

The analyses show excellent agreement with the compositions deduced from the optical properties in the forsterite–fayalite solid solution series. The presence of ferric iron is undoubtedly due to a small admixture of magnetite as impurity in the samples. The low percentages of CaO are

noteworthy. This shows that the olivines belong to the forsterite–fayalite series, and that monticellite is absent. Fayalitic olivines from Skaergaard in Greenland show the same low values for CaO, and Deer and Wager (1939) note a discrepancy between the actual weight percentage CaO in the analysed olivines and the theoretical values deduced from the system $CaO–FeO–SiO_2$. In one, a rock containing 9·05 % CaO, the lime content of the fayalite was 2·18 % instead of a theoretical value of 6–7 %.

It is known from the work of Bowen, Schairer, and Posnjak (1933) that the lime-iron-olivine ($CaFeSiO_4$) and fayalite (Fe_2SiO_4) form a series of solid solutions with a minimum. The relationship between monticellite ($CaMgSiO_4$) and forsterite (Mg_2SiO_4) is not fully known. In their investigation of the system $CaO–MgO–SiO_2$, Ferguson and Merwin (1919) state that monticellite takes up forsterite in solid solution to the extent of about 10 %. Bowen, Schairer, and Posnjak (1933) refer to the identical crystal structures of monticellite and forsterite as determined by Bragg and Brown (1926), and Brown and West (1927), but doubt whether complete solid solution exists between them. The evidence from rocks appears to favour the view that, under igneous conditions, there is little lime present in either the forsteritic or the fayalitic olivines, and that, where present, monticellite is of replacement origin.

Acknowledgements.—The writer is glad of the opportunity to record her indebtedness to Professor F. Walker of the University of Cape Town for his helpful advice and unfailing interest. The cost of the chemical analyses was met by a grant from the Staff Research Fund of the University of Cape Town and this is gratefully acknowledged.

Abstract.—Two olivines from the Spiegel river and Klaasvoogds melilite-basalts of the Cape Province are analysed. Optical properties for the olivines are given. These show excellent agreement with the chemical results. The olivines belong to the forsterite–fayalite series and do not contain significant amounts of Ca_2SiO_4. The presence of nepheline, leucite, analcime, apatite, and zircon in the Klaasvoogds melilite-basalt is described for the first time.

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On the occurrence of anatase in sedimentary kaolin.

By G. Nagelschmidt, H. F. Donnelly, and A. J. Morcom.

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[Read October 7, 1948.]

IT has been shown recently by Brindley and Robinson[1] that anatase could be recognized by X-ray diffraction technique in fireclays from Scotland and Yorkshire which contained from one to two per cent. of titanium dioxide. These authors remark that the anatase appeared to be of a fineness comparable to the kaolin mineral which was the main constituent, and although kaolinites from various sources throughout the world were examined, in no case was either anatase or rutile detected.

The object of this note is to draw attention to the presence of anatase in the sedimentary kaolins of Georgia and perhaps South Carolina, U.S.A. According to Smith[2] 115 kaolin samples from Georgia had on an average 1·13 % of TiO_2 by chemical analysis. The values ranged from 0·5 to 2·2 % of TiO_2. This is in marked contrast to most primary kaolins; those of Cornwall and Devon, for instance, have as a rule below 0·2 % of TiO_2.

In the course of an X-ray survey of various kaolin samples, it was found in this laboratory that a commercial sample of kaolin from Georgia gave a good kaolinite X-ray pattern. The chief constituent was clearly kaolinite and not one of the types intermediate between kaolinite and halloysite observed in fireclay, for which X-ray data have been given by Brindley and Robinson.[3] But extra lines were present in the diagrams which corresponded to the strongest anatase lines. A fraction below 0·2 micron equivalent diameter prepared by centrifuge separation showed a rather stronger anatase pattern and had, by chemical analysis, 5·7 % of TiO_2.

Electron micrographs of this fraction (figs. 1 and 2) show numerous dense particles of 0·05 to 0·2 micron diameter. These particles tend to

[1] G. W. Brindley and K. Robinson, Min. Mag., 1947, vol. 28, pp. 244–247.

[2] R. W. Smith, Bull. Geol. Surv. Georgia, 1929, no. 44.

[3] G. W. Brindley and K. Robinson, Trans. Brit. Ceram. Soc., 1947, vol. 46, pp. 49–62. [M.A. 10–367.]

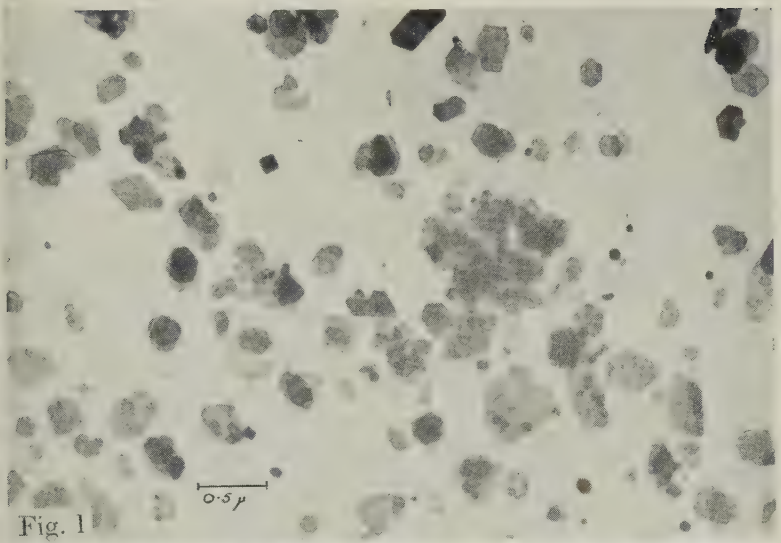

Fig. 1

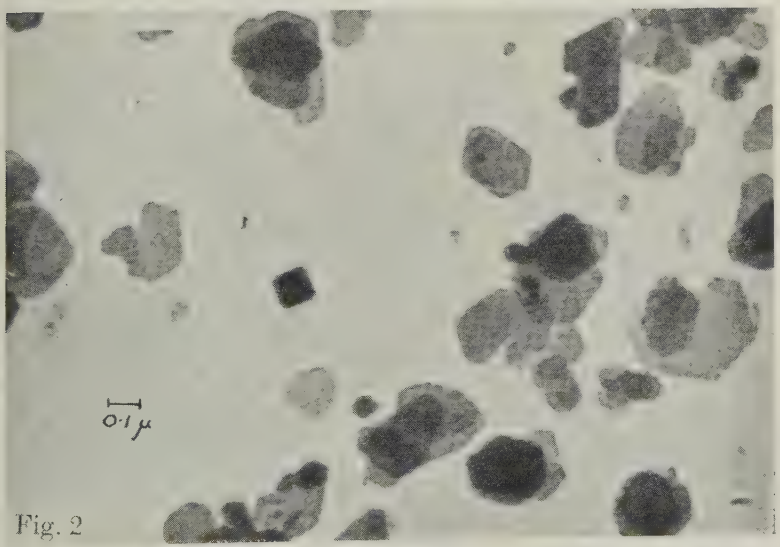

Fig. 2

Electron micrographs of Georgia kaolin no. 5, fraction below 0·2 μ.
Fig. 1, ×18,000. Fig. 2, ×42,000.

be isometric with rounded, hexagonal, or square outline. Well-defined square particles like the one in the centre of fig. 2 are rare. These particles are denser than the hexagonal shapes of the kaolinite plates of similar or larger size shown in the same figure. Electron micrographs of fractions of comparable size from kaolinite samples from Cornwall do not show particles of this type. The higher density can be caused by greater thickness of the particles or by the higher scattering power of the titanium atoms in them. Both causes are probably active. It appears likely that these dense particles are anatase.

In order to follow this observation in more detail, six more commercial samples of kaolin from Georgia or South Carolina were examined. Fractions below 0·2 micron were prepared by centrifuge separation and the samples and fine fractions were analysed for titanium dioxide. The chemical analyses were done by colorimetric determination of the pertitanic acid in sulphuric acid, after a sodium carbonate fusion of the clay. The results are given in table I.

TABLE I. Titanium content of seven samples of sedimentary kaolin.

Sample.	TiO_2 % in whole sample.	TiO_2 % in fraction under 0·2 micron.
Georgia 1	1·3	0·8
„ 2	1·6	0·8
„ 3	1·6	1·6
„ 4	1·4	3·6
„ 5	2·3	5·6
„ 6*	2·0	2·4
South Carolina 1	1·2	1·7

* The sample marked no. 6 from Georgia was prepared in this laboratory from a coarser kaolin from Dry Branch, Georgia, kindly given us by Dr. R. E. Grim. The original sample had 1·6 % TiO_2.

All the samples showed anatase lines on X-ray diagrams and there was a reasonable agreement between the relative intensities of certain anatase lines and the analytical data.

The figures given in table I are not easy to interpret. If anatase is the stable form of titanium dioxide formed as a weathering product of titanium from primary minerals, then one might expect it to be concentrated in a fraction of particles of small size such as the one below 0·2 micron. Such a concentration seems to occur to a small extent in some but not in all of the samples.

As the fraction below 0·2 micron only represents from two to ten per cent. of the clays it is quite obvious that only a small portion of the total titanium occurs in this fraction.

A further sample of Georgia kaolin was split into six fractions by repeated decantations and the six fractions were analysed for titanium with the results given in table II.

TABLE II. Titanium contents of fractionated Georgia kaolin, no. 7.

Size of fraction in microns.	% TiO_2.
+ 10	0·8
5–10	1·0
2·5–5	1·2
1–2·5	1·7
0·5–1	1·9
below 0·5	2·6

This shows a regular small increase with decreasing particle size. Further data, which need not be given in detail here, also lead to the conclusion that the bulk of the anatase is distributed throughout the kaolin and not concentrated in any particular size fraction.

V. M. Goldschmidt[1] gives the value of 0·73 % TiO_2 (0·44 % Ti) as average for the composition of clay-sand sediments as well as of igneous rocks. Compared with this value, the titanium content of Georgia kaolin is high and that of kaolin from Cornwall and Devon is low.

Our thanks are due to the Directors of English Clays Lovering Pochin & Co. Ltd., for permission to publish this work.

Abstract.—The occurrence of anatase in sedimentary kaolins from Georgia, U.S.A., is described on the basis of chemical, X-ray, and electron microscope studies. The anatase is of a size comparable to kaolinite which forms the chief constituent of the clays, but there is a slight tendency for it to be concentrated in the smallest size classes.

[1] V. M. Goldschmidt, Geochemische Verteilungsgesetze der Elemente. IX. Skrift. Norsk. Vid. Akad. I. 1938, for 1937, no. 4. [M.A. 7–166.]

An optical and X-ray examination of the basic-slag mineral silicocarnotite.

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Department of Mineralogy and Petrology, University of Cambridge.

[Read October 7, 1948.]

BLUE pleochroic crystals obtained from basic slag were first described by Carnot and Richard.[1] They published a chemical analysis, some of the optical properties, and a brief description of the forms they observed. The crystals were stated to be orthorhombic, with a composition of $5CaO.P_2O_5.SiO_2$. Several authors[2] later described similar crystals. None, however, gave a thorough account of the optical properties. These various papers were summarized and discussed by Kroll,[3] who accepted Carnot's formula, but concluded, from Bücking and Linck's examination, that the material was monoclinic. Kroll applied the rather unfortunate term 'silico-carnotite' to these crystals.

The present work shows that silicocarnotite occurs in only one modification—orthorhombic. The crystals drawn by Bücking and Linck and described as monoclinic are, in fact, identical with our orthorhombic crystals.

Silicocarnotite is found in basic slags rich in phosphorus. If the slag is not too fine-grained the mineral can be seen as clear blue grains with lens or naked eye. In thin section large areas of grains commonly show preferred orientation. Crystals are rare and are usually very small and show few forms. A number of different samples were examined in the course of the present work and are listed below according to their source and habit.

Source and general description of samples.

A. Granular material showing no definite faces. This was separated by the usual methods from a slag. (Specimen 50068, Dept. Min. Pet.)

[1] A. Carnot and A. Richard, Bull. Soc. Min. France, 1883, vol. 6, p. 237.

[2] J. E. Stead, C. H. Ridsdale, and H. A. Miers, Journ. Chem. Soc., 1887, vol. 51, p. 601. H. Bücking and G. Linck, Stahl und Eisen, 1887, vol. 4, p. 245. G. Hilgenstock, Stahl und Eisen, 1883, vol. 3, p. 498.

[3] V. A. Kroll, Journ. Iron and Steel Inst., 1911, vol. 84, p. 126. [Min. Mag. 19-349.]

B. Occasional small blue crystals from vugs in a fine-grained slag.

C. Idiomorphic crystals embedded in monticellite. This was the only colourless sample examined. (Slide 48749, Dept. Min. Pet.) These three samples (A–C) were kindly supplied by Dr. S. O. Agrell, Department of Geology, University of Manchester.

D. Slag powder containing small blue grains and occasional crystals of silicocarnotite. This was Miers's original material (B.M. 1919,64). Later we received three small crystals picked out from this same British Museum sample.

E. Blue plates and blades (B.M. 1919,67). Short pseudo-hexagonal prisms and elongated prisms (B.M. 1919,70). These two specimens were kindly sent us from the British Museum collection by Dr. F. A. Bannister.

F. Blue blade-like crystals on slag (P 157–9, Rothamsted). These were kindly provided by Dr. E. M. Crowther of the Rothamsted Experimental Station.

G. Synthetic silicocarnotite powder from the Building Research Station, Garston, through the courtesy of Mr. R. W. Nurse.

Habits observed, or nature of material.

1. Prismatic (fig. 3).
2. Plates (001) (fig. 4).
3. Blades (101) elongated along [010], often showing existence of skeletal growth (fig. 5).
4. Small grains or powder showing no crystal shape.
5. Short pseudo-hexagonal prisms and prisms with lozenge-shaped cross-section. Only examined when mounted in slides.
6. Long colourless pseudo-hexagonal prisms.

Chemical composition.

A sample was separated from a slag (sample A) of sufficient coarseness for the blue grains to be seen in the hand-specimen. In section large areas of grains have a similar orientation, and are associated with considerable amounts of black magnetic iron oxide and minor amounts of pale-brownish steadite, a silica-containing apatite.

The results of the chemical analysis are given in table I, column 2, together with the analyses of other authors, and the ideal composition for $5CaO.P_2O_5.SiO_2$.

TABLE I. Chemical analyses of silicocarnotite.

	1.	2.	3.	4.	5.	6.
SiO_2	12·46	13·64	12·42	10·79	9·47	9·42
P_2O_5	29·44	27·96	29·65	29·15	31·19	30·85
CaO	58·10	56·78	53·20	56·58	57·42	57·60
MgO	—	trace	trace	0·74	trace	—
FeO	—	—	1·80	—	0·95	2·94
MnO	—	0·03	trace	0·21	trace	—
Al_2O_3	—	0·41	2·76	—	1·13	—
Fe_2O_3	—	1·66*	—	1·00	—	—
S	—	—	—	0·05	—	—
V	—	—	—	1·64	—	—
NiO	—	—	—	0·04	—	—
	100·00	100·48	99·83	100·20	100·16	100·81
Sp. gr. ...	—	3·06	3·042	—	3·06	—

* Total iron as Fe_2O_3 (chiefly impurity).

1, Theoretical for $5CaO.P_2O_5.SiO_2$. 2, Riley and Segnit (this paper). 3, Carnot and Richard (1883). 4, Stead and Ridsdale (1887). 5, Bücking and Linck (1887). 6, Hilgenstock (1883).

The composition $5CaO.P_2O_5.SiO_2$ lies on the binary system Ca_2SiO_4–$Ca_3P_2O_8$. Several phase diagrams have been proposed for this system.[1] The synthetic work indicates that silicocarnotite has a rather limited range of stability and over this range forms solid solutions. Further evidence of this is to be seen in the zoning of our analysed material. This accounts for the differences in composition shown in table I.

In our analysis the iron oxide is chiefly contained as impurity; a small amount of it remained as inclusions in the silicocarnotite grains. Omitting minor constituents (the alumina can be grouped with silica, and manganese with lime) the analysis can be calculated to $5{\cdot}2CaO.P_2O_5.1{\cdot}15SiO_2$, or, recalculating on the basis of 12 oxygen atoms, we get $Ca_{4{\cdot}96}P_{1{\cdot}93}Si_{1{\cdot}11}O_{12}$, which is close to the theoretical $Ca_5(P,Si)_3O_{12}$. An interesting property of the mineral is its solubility in organic acids. This property of basic-slag phosphates was known before any examination of the constituent minerals took place. Ground slag has consequently been used directly as a plant fertilizer since the latter half of the nineteenth cen-

[1] R. L. Barrett and W. J. McCaughey, Amer. Min., 1942, vol. 27, p. 680. [M.A. 8–312.] G. Trömel, Stahl und Eisen, 1943, vol. 63, p. 21. M. A. Bredig, Amer. Min., 1943, vol. 28, p. 594. [M.A. 9–92.]

tury. The specific gravity was determined by suspension in methylene iodide.

X-ray examination.

In view of the strikingly different habits exhibited by the crystals, it was thought desirable to examine a number of specimens in order to

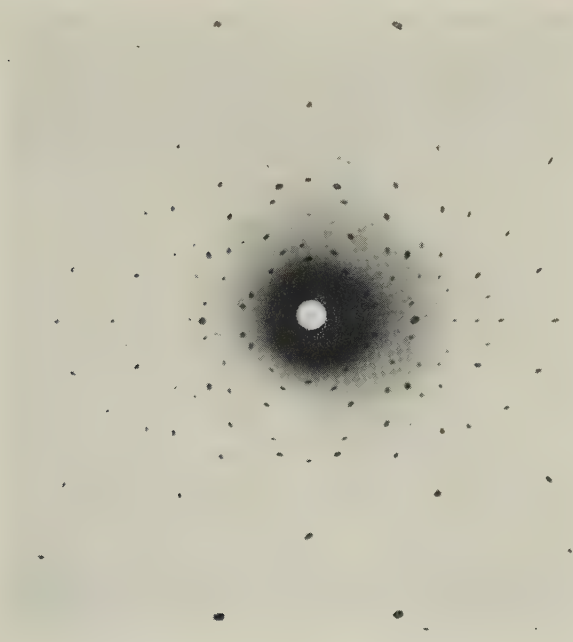


FIG. 1. Laue photograph of single crystal of silicocarnotite, showing orthorhombic symmetry.

ascertain whether they were crystallographically identical. The habit, in a number of cases, made it difficult to establish the symmetry and, at first sight, the possibility of dimorphism could not be excluded.

Laue and oscillation photographs were taken of single crystals of the following sources and habits; B1, D1, E2, E3, F3, following the nomenclature given above. All these crystals were shown to be identical crystallographically and to have orthorhombic symmetry, *mmm*. In addition, powder photographs in both 9-cm. and 19-cm. diameter cameras were taken of the following specimens, A4, D1, D4, E2, G4. These photographs were identical apart from very minor differences not to be ascribed to differences in crystal-structure. The X-ray examination

Fig. 2.

therefore showed that the synthetic material was identical with that found in slags of different sources, and that the marked difference in habit observed had no structural significance. The dimensions of the orthorhombic unit cell are:

$$a\ 10{\cdot}1,\ b\ 6{\cdot}7,\ c\ 15{\cdot}4\ \text{Å}.;\ a:b:c = 1{\cdot}51:1:2{\cdot}30.$$

The space-group is probably *Pnnn*. The unit-cell molecular weight corresponding to the measured density of 3·06 is 1930, in good agreement with the molecular weight 1925 of four ideal formula units $5CaO.SiO_2.P_2O_5$.

The X-ray photographs were taken with nickel-filtered Cu-$K\alpha$ radiation. One of the Laue photographs was particularly good and is reproduced in fig. 1, as is the best of the powder photographs (fig. 2). In table II are listed the spacings of the lines observed on the powder photograph of specimen A4 taken in a 19-cm. diameter camera with filtered Cu-$K\alpha$ radiation, λ 1·54 Å.

Morphology.

1. *Prismatic.*—The crystals from samples B and D were essentially similar. They are minute, stout, orthorhombic crystals less than 0·5 mm. in length, and are evidently closely similar to those which Miers examined. They are also similar to those illustrated by Bücking and Linck, and Carnot's crystals were probably of this type. Our crystal from B is depicted in fig. 3. The crystal examined from D did not show the (100) face.

We have chosen the same orientation of axes as Miers, and the axial ratios as determined by X-ray methods, $a:b:c = 1{\cdot}51:1:2{\cdot}30$, agree well with his values derived from goniometrical measurements, 1·5023 : 1 : 2·2943. The X-ray and morphological unit-cells are thus identical. Approximate values of the interfacial angles are given below, together with the corresponding measurements by other authors.

	Riley and Segnit.	Miers.	Bücking and Linck.	Carnot.
(100):(101)	57°	56° 47′	56° 46′	—
(101):(001)	33	—	—	—
(101):(10$\bar{1}$)	66	66 26	—	66° 50′
(110):(1$\bar{1}$0)	64	67 11	63 3	64 —

TABLE II. X-ray diffraction lines of silicocarnotite; d in Å.

8·516	2·030	1·403	1·133	0·974	0·851
7·763	2·003	1·393	1·123	0·968	0·849
5·610	1·955	1·381	1·117	0·961	0·847
5·272	1·893	1·364	1·107	0·956	0·845
4·542	1·881*	1·355	1·100	0·953	0·841
4·047	1·865	1·341	1·097	0·950	0·839
3·912	1·846	1·330	1·092	0·941	0·834
3·782	1·851	1·319	1·089	0·939	0·832
3·581	1·781	1·311	1·086	0·934	0·830
3·289*	1·747*	1·305	1·079	0·933	0·828
3·181*	1·733	1·292	1·072	0·930	0·825
3·080*	1·692	1·278	1·064	0·928	0·822
3·010*	1·672	1·261	1·059	0·924	0·816
2·953*	1·643	1·247	1·056	0·924	0·814
2·819†	1·623	1·240	1·052	0·921	0·808
2·706	1·602	1·234	1·043	0·908	0·807
2·603*	1·581	1·228	1·036	0·905	0·805
2·574*	1·558	1·216	1·030	0·903	0·803
2·534	1·544	1·211	1·027	0·899	0·801
2·459	1·532	1·201	1·024	0·897	0·798
2·340	1·515	1·195	1·013	0·876	0·796
2·335	1·505	1·192	1·001	0·874	0·794
2·295	1·501	1·184	0·996	0·871	0·792
2·269	1·494	1·172	0·994	0·870	0·785
2·219	1·478	1·160	0·991	0·865	0·783
2·170	1·464	1·156	0·987	0·863	
2·106	1·447	1·140	0·983	0·855	
2·077	1·411	1·136	0·979	0·853	

* lines of approximately equal intensity.
† strongest line, probably 220.

All spacings were calculated using λ Cu-$K\alpha$ = 1·5418 Å. (weighted mean of α_1 and α_2). Each line in an α-doublet was recorded separately and appears in the table under its own apparent spacing. The first four highest spacing lines are 101, 002, 110, and 200.

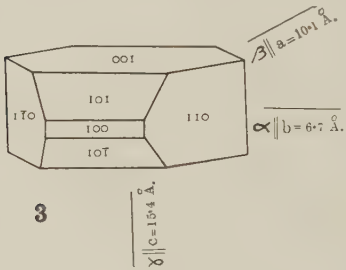
2. *Plates.* –These thin but large (up to 2 mm. square) plates of habit (001) were predominant in sample E. They show a perfect (010) and a poor (100) cleavage. The obtuse bisectrix γ is normal to the principal face (001) of the plates. The perfect (010) cleavage gives two parallel straight edges to the plates (fig. 4), while the poor (100) cleavage is sometimes seen at right angles to the other. Occasional fragments are rectangular.

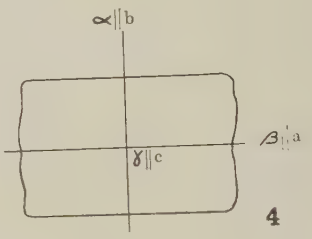
3. *Blades.*—These thin blades of habit (101) are elongated parallel to the b-axis, and often show evidence of skeletal growth. The perfect (010)

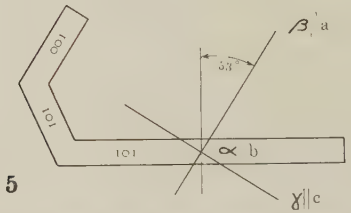
FIG. 2. X-ray powder photographs of silicocarnotite, taken in a 19-cm. diameter camera with filtered Cu-$K\alpha$ radiation. One-half of the film only is shown.

cleavage is once more exhibited. A cross-section of a typical crystal is drawn in fig. 5, which also shows the orientation of the optical indicatrix. These blades were the main constituent of sample F, and they were also observed in sample E.

4. The separated grains showed no recognizable crystallographic faces and no significant observations were possible.







FIGS. 3–5. Crystals of silicocarnotite, showing optical orientation. (In fig. 3 the indices refer to faces intersected by the plane of section.)

5. A few crystals from E were examined only when mounted in microscope slides. In one case they appeared to be short pseudo-hexagonal prisms as viewed down the *b*-axis and were almost certainly orthorhombic. In the other case, they were long needles of lozenge-shaped cross-section elongated along the *b*-axis.

6. The long colourless pseudo-hexagonal prisms were observed in a slide of sample C. The crystals are elongated along the *b*-axis.

Optical properties.

The best measurements were obtained from the (001) plates (fig. 4) to which the obtuse bisectrix γ is normal. The relation of the optical scheme to the crystallographic axes is:

$$\alpha \parallel b, \ \beta \parallel a, \ \gamma \parallel c.$$

The optic orientations of the plates and blades are given in figs. 3–5.

The plates give a good interference figure, and the optic axial angle about γ was measured on the universal stage using filtered mercury light owing to the rather strong dispersion. The average of a large number of measurements gave:

$$2V\ 94\tfrac{1}{2}^\circ \text{ (yellow)}, 94^\circ \text{ (green)}, 92\tfrac{1}{2}^\circ \text{ (blue)}.$$

Hence the optic sign is negative with dispersion $r < v$ marked. The refractive indices, as determined in sodium-light (α and β from the plates directly, γ as a maximum on crushed grains), are:

$$\alpha\ 1{\cdot}641,\ \beta\ 1{\cdot}653,\ \gamma\ 1{\cdot}663 \pm 0{\cdot}002.$$

The pleochroism is very striking. The crystals are a clear blue colour, and the change from blue to colourless is readily seen by the naked eye by rotation in polarized light. The pleochroism scheme is α bright blue, β pale greyish-blue or colourless, γ light blue or colourless, absorption $\alpha > \beta > \gamma$.

The pleochroism and colour of the analysed material are weak in sections of normal thickness, but are sufficient to show the colour zoning of the grains; inner zones are colourless, outer pale blue. Marked dispersion is shown near the extinction positions in sections cut nearly normal to an optic axis, as well as in the interference figure. The optic axial angle measured in sodium-light varied in individual sections from 76° about γ to 84° about α. Of zoned crystals, the inner parts have the lower 2V about γ.

Table III summarizes the optical properties of a selection of specimens. The minimum and maximum refractive indices are α 1·639, γ 1·677±0·002. The birefringence is somewhat less than indicated by this owing to variation in composition of grains.

TABLE III. Optical properties of silicocarnotite.

Sample and habit.	Refractive Indices α.	β.	γ.	Axial angle and sign.	Dispersion.
A4	1·639	—	1·657	+75° to −84°	$r > v$ marked
E2	1·641	1·655	1·663	−85° (Na-light)	„ „
D1	1·648	—	1·669	−80° to −85°	$r < v$ rather weak
B1	1·642	—	1·661	+80° to +85°	$r < v$ weak
C6	1·640	—	1·658	+77°	very weak
F3	1·660	—	1·677	−80°	—

All refractive index measurements ±0·002.

Effect of heat.

In an endeavour to gain some idea of the temperature of a possible phase transition, a number of samples were heated and then examined

optically and by X-ray powder photographs. Experiments with their results are as follows:

1. Silicocarnotite powder (sample A) heated to 1330° C. The only change was the disappearance of the blue colour. This was a characteristic change of the material and occurred in all the following cases. The X-ray powder photographs of the heated and unheated material were identical in all respects.

2. Further sample of A heated to 1450°. The product was a fine grey powder. Under the microscope a phase change was evident—grains were broken and showed fan extinction and fine multiple twinning. A careful comparison of the powder photograph given by this specimen with that of the unheated material showed slight but probably significant differences. The new structure must therefore be very closely related to the old.

3. A slab of the original slag from which A was separated was heated to 1400° C. A thin section showed a breaking up of the grains into smaller units, and undulose extinction over the larger original grain areas. Zoning was no longer evident, and 2V was determined as 83° positive. The small broken grains, however, appear homogeneous and do not show any change.

4. A clear blue plate, E2, about a millimetre square was first heated to 1330°. Apart from decolorization there was no change. The plate was further heated to 1450°. At this temperature it had broken down to a fine powder, and the grains showed broad twinning bands and irregular extinction.

5. Blades, F3, showed a similar reaction to the plate mentioned above.

These experiments indicate that a change certainly takes place below 1450° C., and probably above 1400° C.

Acknowledgements.—We desire to record our thanks to Professor C. E. Tilley for bringing the problem to our notice, and for his constant help; and also to Mr. K. Rickson for his assistance in the X-ray work.

Clinozoisite from Camaderry Mountain, Co. Wicklow.

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[Communicated by Professor C. E. Tilley; read October 7, 1948.]

1. *Nature of the occurrence.*

THE clinozoisite to be described is found in veins traversing a metamorphosed basic intrusion exposed at the top of Camaderry Mountain, Glendalough, Co. Wicklow. This intrusion is a small boss of Lower

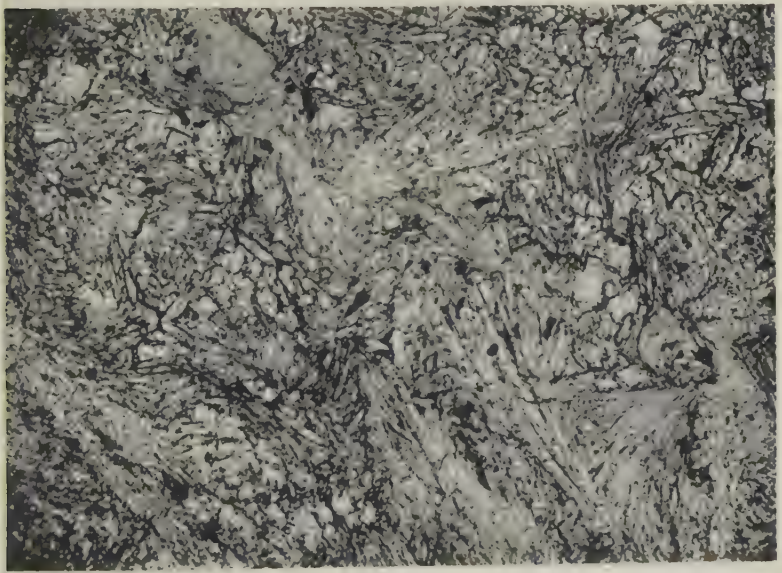

Fig. 1. Zoisite-amphibolite. ×25. This is the metamorphosed igneous rock through which the veins of clinozoisite and albite run. Small grains of zoisite and clinozoisite are enfolded by radiating fibres of tremolite. Sphene is a common accessory mineral.

Palaeozoic age which has been metamorphosed both by earth movement and by the intrusion of the Leinster granite. The rock exposed is now an amphibolite (fig. 1) within which are found the veins carrying clinozoisite with albite and a little prehnite, sphene, and tremolite.

These veins, which are up to an inch in width, were probably introduced during the late stages of the basic intrusion as veins of lime-rich plagioclase.

Preliminary examination under the microscope shows that the clinozoisite is well crystallized, fresh, and free from inclusions. The colour in the hand-specimen is grey-white; in thin section it is colourless. Individual crystals are found up to 5 mm. in length. Twinning and intricate zoning are common.

2. *Specific gravity and separation.*

The clinozoisite was separated from the other minerals of the vein by the use of heavy liquids and the centrifuge. A section of the vein was first broken down and passed through a 90-mesh sieve, then panned to remove the dust. Methylene iodide diluted to a specific gravity of 3·00 floated off the albite, prehnite, and amphibole. Next a liquid of specific gravity 3·40 was used to separate the clinozoisite from the sphene.

By a gradual reduction of the specific gravity of this last liquid it was found possible to separate the grains of clinozoisite into two fractions. The specific gravity of the liquid which effected this separation was determined as 3·372 at 18° C. The average specific gravities of the two fractions were 3·370 and 3·375 at 18° C.

3. *Optical properties.*

The intricate zoning of many of the crystals presents a variety of optical properties within a single specimen. Values for the refractive indices, double refraction, optic axial angle, and extinction angle $\alpha:c$ were measured for the central and outside zones.

Table I. Optical data.

Central zones.			Outer zones.		
α	...	1·710	α	...	1·712
β	...	1·712–1·713	β	...	1·715–1·716
γ	...	1·716	γ	...	1·719
$\gamma-\alpha$	...	0·006	$\gamma-\alpha$	...	0·007
$2V\gamma$	...	14–20°	$2V\gamma$	...	68–78°
$\alpha:c$	...	50–60°	$\alpha:c$	...	3–10°

These readings were made in monochromatic mercury yellow light (579 $\mu\mu$). The refractive indices are subject to an error of $\pm$0·002. The central zones correspond to the lighter fractions (sp. gr. 3·370) and the outer zones to the heavier (sp. gr. 3·375). Values for 2V and $\alpha:c$ were measured on a Fedorov stage.

Values of $\alpha:c$ in the crystal shown in fig. 2 were measured for both

halves of the twin, using a mercury lamp with filters for yellow (579 $\mu\mu$) and blue (436 $\mu\mu$). These values for the direction α are represented diagrammatically in fig. 3. In all cases α is in the obtuse angle β.

Figs. 4 and 5 are illustrations of zoned twins similar to that in fig. 3. Note that the boundaries between the zones are sometimes parallel with a crystallographic direction, sometimes irregular.

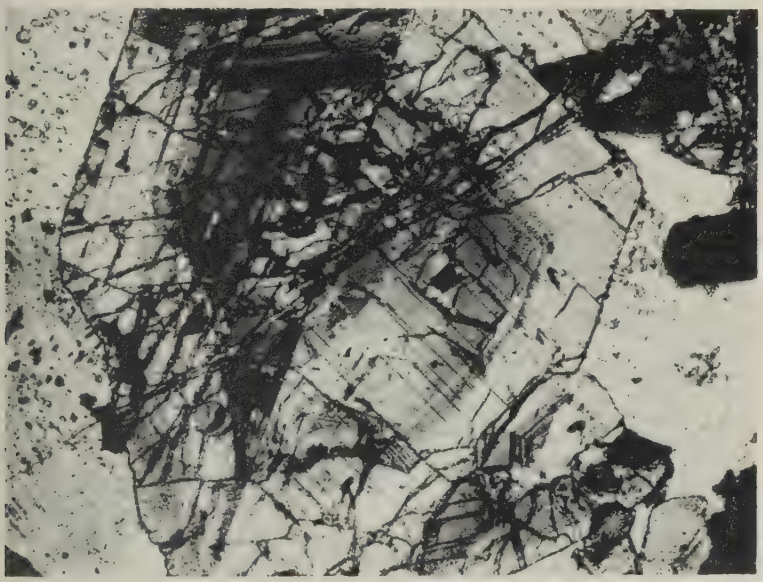

Fig. 2. Clinozoisite from vein. ×25. Crossed nicols. Wratten A (red) filter. A well-developed crystal of clinozoisite surrounded by albite. The twinning, zoning, and cleavages stand out clearly. The interference colours are anomalous—browns, blues, and yellow-blues.

Table II. Measured values for the extinction angle $\alpha : c$.

Fig. 3.—	Left half.			Right half.	
	Yellow.	Blue.		Yellow.	Blue.
	62°	35°	central zone	—	—
	53	30	|	51°	29°
	44	22	|	43	21
	11	9	|	3	3
	17	13	outwards	10	7
	11	9	↓	3	3

Note that the small central area with the high-extinction values is not present in the right half of the crystal. Note also the reversal of the trend in the one from outermost zone.

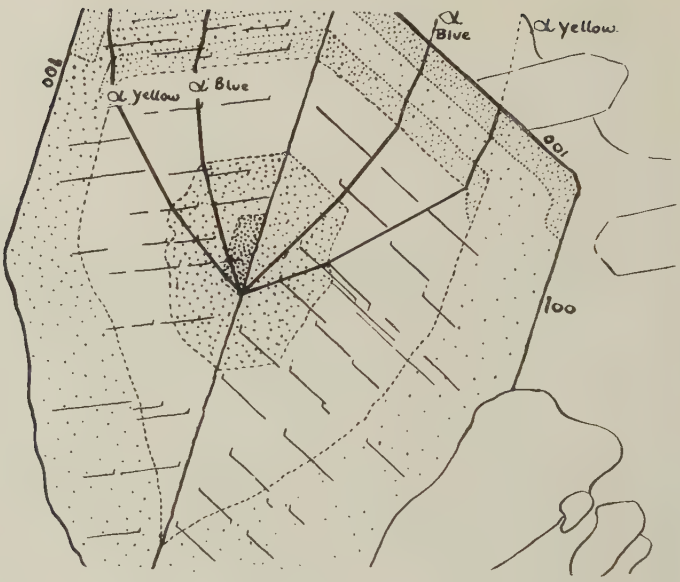

Fig. 3.

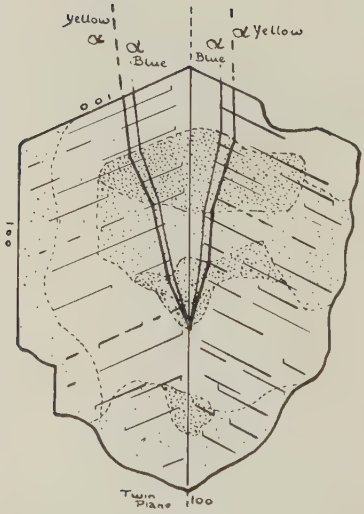

Fig. 4.

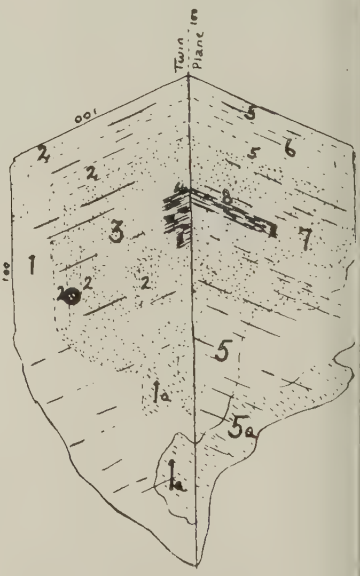

Fig. 5.

Figs. 3–5. Twinned and zoned crystals of clinozoisite, showing extinction directions.

TABLE II (*cont.*).

Fig. 4.—	Left half.			Right half.	
	Yellow.	Blue.	Zone.	Yellow.	Blue.
	23°	20°	Heavy stipple	16°	10°
	11	11	Light stipple	3	3
	8	8	Plain	−3	−1

Fig. 5.—	Left half.			Right half.	
Zone.	Yellow.	Blue.	Zone.	Yellow.	Blue.
1*a*,	7°	7°	5*a*,	−3°	−5°
1,	11	10	5,	1	0
2,	17	13	6,	5	4
3,	41–51	22–27	7,	15–30	12–17
4,	67	47	8,	42	28

The graph (fig. 6) shows that the values for 2V and $\alpha:c$ are related to one another in a definite manner. Since the data are drawn from

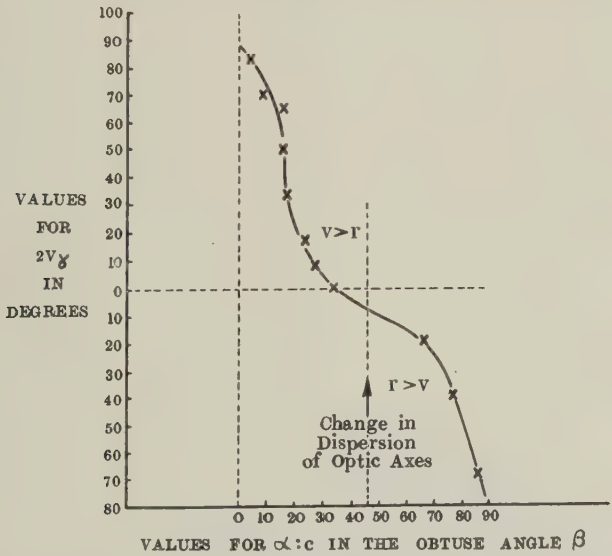

FIG. 6. Graph showing the trend in the relationship between 2V and $\alpha:c$ in clinozoisite.

only two sources, Orlov and this paper, the curve must be regarded as provisional and indicative of the trend of the relationship only.

When the physical and optical properties of the clinozoisites are plotted (fig. 7) against the total iron content expressed as Fe_2O_3 it is

found that the values for the refractive indices, double refraction, and specific gravity respond regularly to a change in the percentage of Fe_2O_3, but that the values for 2V and $\alpha:c$ behave in an irregular manner when

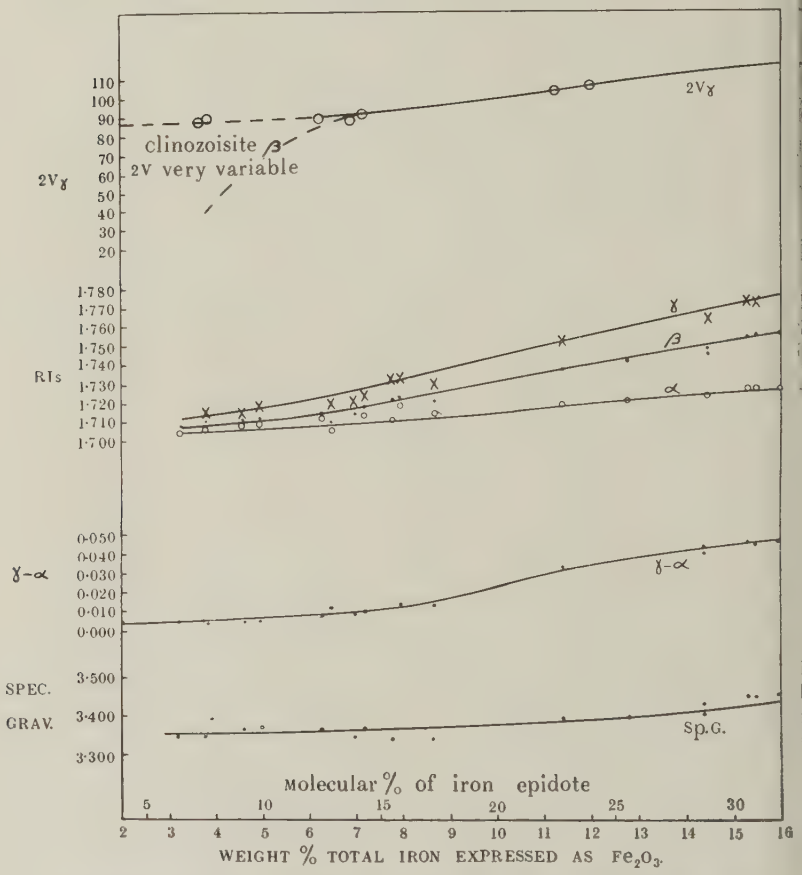

FIG. 7. The physical properties of the epidote-clinozoisite series plotted against the total content of iron expressed as Fe_2O_3.

the tenor of Fe_2O_3 drops below about 5 %. Possibly the physical conditions prevailing at the time of crystallization exerted a greater influence on these properties than a change in the content of iron.

Dispersion of the optic axes.—The dispersion of the optic axes is very variable. Observations on the Camaderry material show that it is feeble $v > r$ in the outer zones where the $\alpha:c$ angle is small, but that it

becomes strong in the central zones as the extinction angle increases, changing in character to $r > v$. Accurate observations were made by Orlov who stated that the maximum dispersion occurs when $2V_\gamma$ is about zero. It reaches a maximum value of about 20°. The change from $v > r$ to $r > v$ takes place when $\alpha:c$ reaches about 45°.

Elongation.—The crystals of clinozoisite are normally elongated parallel with the crystallographic axis *b*. Examples which show a marked zonary structure sometimes display a difference in the sign of elongation for the centre and outer zones. This is caused by the rotation of the ellipsoid bringing α or γ more nearly transverse to the elongation.

4. *Chemical analyses.*

The chemical analyses of the two fractions presented no unusual features. The H_2O content was tenacious but came off successfully when heated with an oxy-coal-gas blow-lamp. The results are given in table III.

TABLE III. Chemical analyses of clinozoisite.

1. Fraction of average specific gravity 3·370 representing the inner portion of the zoned crystals.
2. Fraction of average specific gravity 3·375 representing the outer portions of the zoned crystals.

	1.	Mol. props.	Metal atoms.		2.	Mol. props.	Metal atoms.	
SiO_2	39·08	0·651		6·01	38·01	0·633		5·84
TiO_2	trace	—			trace	—		
Al_2O_3	30·96	0·303	5·59		31·71	0·311	5·74	
Fe_2O_3	4·13	0·026	0·48	6·12	4·68	0·029	0·53	6·30
FeO	0·42	0·006	0·05		0·23	0·003	0·03	
MnO	0·01	—			trace	—		
MgO	0·01	—			0·01	—		
CaO	23·32	0·416		3·86	23·86	0·427		3·94
H_2O+... ...	1·86	0·104	1·94	1·94	1·83	0·103		1·90
H_2O-... ...	0·01				0·01			
Total	99·80				100·34			

The metal atoms are calculated on the basis of 26(O,OH), this being the content of the unit cell. It will be seen that the ratios of the metal atoms agree reasonably well with the accepted empirical formula for the epidote-clinozoisite series $H_2O.4CaO.3(Al,Fe)_2O_3.6SiO_2$.

The structural formula has been studied by L. Waldbauer and D. C. McCann and by T. Ito. The latter gives the following structural formula: $Ca_2O.(Al,Fe)O_2OH.Al.AlSi_3O_9$.

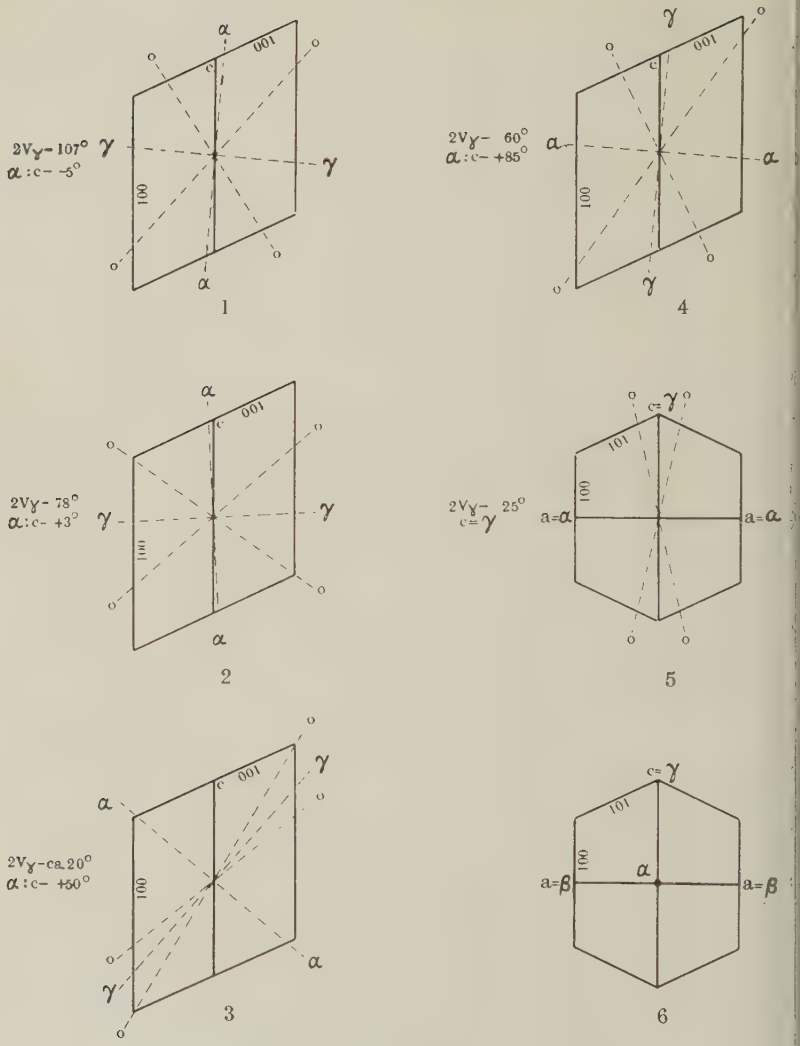

Fig. 8. A comparison of optical orientations.

1. Epidote of Weinschenk (1907).
2. Clinozoisite from Camaderry. Values from the outer portions of zoned crystals. Following Orlov this is clinozoisite-α.
3. Clinozoisite from Camaderry. Values from the inner portions of zoned crystals. Following Orlov this is clinozoisite-β, in which the angle $\alpha:c$ exceeds 45°.
4. Clinozoisite-β of Orlov (1926). Note the similarity to zoisite-β. Any further rotation of the ellipsoid would make the two indistinguishable.
5. Zoisite-β. Weinschenk (1907). This could be regarded as a special case of clinozoisite.
6. Zoisite-α. Weinschenk (1907).

The epidote end-member has a limiting content of Fe_2O_3 of about 16 %, since Fe replaces Al to the fullest possible extent in the formula $Ca_2O.FeO_2OH.Al.AlSi_3O_9$.

5. *Data on the iron-poor members of the epidote-clinozoisite series.*

Fourteen analyses extracted from the literature are listed with the analyses of the Camaderry material for comparison in table IV.

TABLE IV. Data on the iron-poor members of the epidote-clinozoisite series.

Author ...	Weinschenk.	Hietanen.	Orlov.	Zambonini.	Zambonini.	Orlov.	Orlov.	Weinschenk.
Locality ...	Goslerwand.	Finland.	Horky.	Chiampernotto.	Monte-Tovo.	Proseč.	Horky.	Zillerthal.
	%	%	%	%	%	%	%	%
SiO_2 ...	39·06	40·36	38·66	39·16	—	38·61	38·27	38·60
TiO_2 ...	—	0·09	trace	—	—	trace	trace	—
Al_2O_3 ...	32·57	30·67	31·94	30·93	—	31·22	31·69	31·71
Fe_2O_3 ...	1·68	0·61	2·58	3·18	3·01	2·80	3·01	3·52
FeO ...	0·29	1·77	0·61	0·32	0·64	0·96	0·79	0·35
MnO ...	trace	—	0·06	0·17	—	0·07	0·07	trace
MgO ...	—	0·74	0·10	0·08	—	0·10	0·14	—
CaO ...	24·53	22·62	24·39	24·11	—	24·42	24·19	24·22
Na_2O ...	—	—	—	—	—	0·03	—	—
K_2O ...	—	—	—	—	—	trace	—	—
H_2O+ ...	2·01	3·50	1·72	2·18	—	1·69	1·65	1·95
H_2O- ...		—	0·10	0·21	—	0·05	0·09	
F ...	—	—	0·03	—	—	0·02	—	—
Total ...	100·14	100·36	100·19	100·34	—	99·97	99·90	100·35
% Total iron as Fe_2O_3...	2·00	2·56	3·25	3·53	3·71	3·86	3·88	3·90
α ...	1·7176	min. 1·670	1·706	—	—	>1·710	>1·707	1·7238
β ...	1·7195	1·674	1·708–1·710	1·7153	—	1·711–1·713	1·709–1·711	1·7291
γ ...	1·7232	max. 1·681	1·712	—	—	⩽1·716	<1·712	1·7343
$\gamma-\alpha$ ...	0·0056	0·013	0·006	—	—	0·006	0·005	0·0105
$2V\gamma$ ...	81° 40′	31–55°	very variable	—	88° 50′	very variable		89° 16′
$\alpha:c$ ...	2°	—	see graph	2·5–8°	3–6°	see graph		0°
Sp. gr. ...	3·372	3·215–3.230	3·343–3·366	—	—	3·343–3·366		3·3985

Author ...	Johnston.	Johnston.	Forbes.	Shannon.	Lacroix.	Thomas.	Tempel.	Forbes.
Locality ...	Camaderry.	Camaderry.	Huntington.	Trumbull.	Ariège.	Inverness.	Zillerthal.	Zillerthal.
SiO_2 ...	39·08	38·01	37·99	36·89	38·95	39·02	37·80	—
TiO_2 ...	trace	trace	—	—	—	trace	0·10	—
Al_2O_3 ...	30·96	31·71	29·53	28·50	28·90	28·64	27·63	—
Fe_2O_3 ...	4·13	4·68	5·67	5·92	5·75	6·81	7·62	6·97
FeO ...	0·42	0·23	0·53	0·52	1·08	0·34	0·19	0·89
MnO ...	0·01	trace	0·21	0·02	—	trace	0·04	—
MgO ...	0·01	0·01	—	0·21	0·35	trace	0·29	—
CaO ...	23·32	23·86	23·85	27·26	22·80	23·73	24·56	—
Na_2O ...	—	—	—	—	—	—	—	—
K_2O ...	—	—	—	—	—	—	—	—
H_2O+ ...	1·86	1·83	2·04	1·29	1·90	1·76	1·83	—
H_2O- ...	0·01	0·01						—
F ...	—	—	—	0·60	—	—	—	—
Total ...	99·80	100·34	99·82	101·21	99·73	100·30	100·06	—
% Total iron as Fe_2O_3...	4·60	4·93	6·25	6·49	6·94	7·18	7·83	7·95

TABLE IV (*cont.*).

Author. Locality.	Johnston. Camaderry.	Johnston. Camaderry.	Forbes. Huntington.	Shannon. Trumbull.	Lacroix. Ariège.	Thomas. Inverness.	Tempel. Zillerthal.	Forbes. Zillerthal.
α ...	1·710	1·712	1·714	1·706	1·7091–1·7103	1·714	1·712	1·720
β ...	1·712–1·713	1·715–1·716	1·716	1·710	1·7143–1·7149	1·7196	1·723	1·724
γ ...	1·716	1·719	1·724	1·720	1·7200–1·7202	1·725	1·735	1·734
$\gamma-\alpha$ ...	0·006	0·007	0·010	0·014	0·0097–0·0111	0·011	0·023	0·014
$2V\gamma$ ...	14–20°	68–78°	89° 28′	—	86° 29′	90° 25′	—	92° 14′
$\alpha:c$ ...	50–60°	3–10°	2° 9′	—	—	1°	—	0°
Sp. gr. ...	3·370	3·375	3·367	—	3·344	3·37	3·324	—

6. *Conclusion.*

The clinozoisite from Camaderry Mountain is interesting for the variety of optical properties it displays. Whilst these properties have been noted before, especially by Orlov, such large values for $\alpha:c$ and small values for 2V are not usually associated with clinozoisite.

The rapid changes in these values are the result of the rotation of the ellipsoid in the optic axial plane. When the content of iron drops below about 5 %, this rotation of the ellipsoid appears to be much freer and not entirely dependent on the chemical composition. Or if it is the result of chemical change, then the sensitivity to such change must be very much greater in the iron-poor members of the series. Unfortunately the data available are insufficient to be definite about this, but it seems more probable that when the content of iron is low, other factors, such as the temperatures and pressures prevailing during the period of crystallization, may exert a greater influence on the optics than the chemical composition alone.

The similarity between clinozoisite-β with a large $\alpha:c$ extinction angle and zoisite-β as described by Termier is very marked.

In conclusion I should like to thank Professor C. E. Tilley for his very able supervision of my work and Dr. S. R. Nockolds for his encouragement and suggestions.

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